A Multiyear Plan for the

Hydrogen R&D Program

Rationale, Structure, and Technology Roadmaps

Office of Power Delivery
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Energy Efficiency and Renewable Energy
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Cover Photos (from top to bottom)

Photoelectrochemical hydrogen production apparatus. Photo courtesy of John Turner, National Renewable Energy Laboratory.

Conformable carbon wrapped high-pressure storage tanks. Photo courtesy of Thiokol Propulsion and Lawrence Livermore National Laboratory.

Testing of a Hydrogen Fuel Cell assembly, from left to right, Dr. Peter Lehman, Humbolt University; Dennis Whitmer, University of Alaska; and Dr. Jay Keller, Sandia National Laboratories. Photo courtesy of Dr. Jay Keller.

Hydrogen R&D Program Roadmap
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Executive Summary

The use of hydrogen in the National energy infrastructure has been suggested for more than two decades. Hydrogen can add flexibility to our energy consumption pattern; however, this consideration alone is not sufficient to lead to the large-scale introduction of hydrogen technologies.

There are no major commercial energy markets for hydrogen and current use is limited mainly to the petroleum industries. For both economic and environmental reasons, the Hydrogen Program has developed a strategy with the potential to allow hydrogen to become a major energy commodity.

Achieving the goals of the Hydrogen Program will require advances in production, storage, and conversion technologies before multiquad uses are feasible. This multiyear plan has been developed by the U.S. Department of Energy to provide overall guidance and leadership for the Core R&D Program, and documents the critical research projects that can make significant contributions to the development and validation of competitive hydrogen energy systems. It identifies areas where the research is nearer-term and where the technology will not be available until the longer-term.

The longer-term nature of this program allows integration of the results of portfolio analysis and various future energy scenarios to ensure the appropriate mix of technology projects to meet strategic goals.

1.0 Introduction

This Technology Roadmap highlights the U.S. Department of Energy's Hydrogen Research and Development Program and documents the strategic objectives to both improve existing technologies and discover new technologies in the areas of production, storage and utilization. Hydrogen's potential value lies primarily in serving as a versatile energy carrier whose consumption at the point of use occurs with little or no pollution and, in some applications, with high efficiency. The challenge for the R&D program is characterized by comparing nearer-term technology options with mid- and longer-term approaches in an effort to meet the cost and performance goals necessary to introduce hydrogen as a competitive technology.

> **A Challenge for the 21st Century**
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> The United States faces major energy-related challenges as it enters the twenty-first century. Our economic well-being depends on reliable, affordable supplies of energy. Our environmental well-being—from improving urban air quality to abating the risk of global warming—requires a mix of energy resources that emit less carbon dioxide and other pollutants than today's mix does. Our national security requires secure supplies of oil or alternatives to it, as well as prevention of nuclear proliferation. And for reasons of economy, environment, security, and stature as a world power alike, the United States must maintain its leadership in the science and technology of energy supply and use. **President's Committee of Advisors on Science and Technology, September 30, 1997.**

This Technology Roadmap is a stand-alone document designed to communicate the activities, direction, and milestones of the Core R&D activities funded by the Program. The information contained in Sections 1 and 2 is presented to provide the justification for hydrogen energy research; Sections 3 and 4 describe the Program's funded activities. This document also complements other programmatic reports developed by the DOE Hydrogen Program, including the Strategic Plan, Annual Operating Plan, Technical Review Report, and Technology Validation Plan.

The goals of the DOE Hydrogen R&D Program are to facilitate the successful transition of hydrogen energy production from fossil fuel-based sources (primarily natural gas) to renewable energy-based sources (including solar, wind and biomass) and to cost-share with industry the validation of production, storage and end-use technologies leading to commercialization. The Program's near-term focus as a transition strategy for the production of hydrogen is steam reforming of abundant, inexpensive natural gas. The resulting cost-competitive hydrogen fuel increases the probability that hydrogen systems will be successfully introduced into many sectors of the economy and become competitive with fossil fuel-based systems. This will support the introduction of renewable hydrogen systems and drive further technology development due to market forces.

Natural gas is the second largest primary energy resource consumed in the United States after petroleum. Total natural gas production in 1996 was 19 trillion cubic feet, almost a 3 trillion cubic feet increase over ten years. This increase has been stimulated in part by the low average price for natural gas of nearly two dollars per thousand cubic feet at the wellhead and by increased commercial sector consumption for the purpose of reducing pollution emissions. Although natural gas produces carbon dioxide when combusted, these emissions are dramatically lower compared to other fossil sources such as coal and oil.

Hydrogen, like natural gas, can be used as a gaseous fuel in traditional energy applications. Unlike natural gas, hydrogen is not found in nature and requires the expenditure of primary energy to produce it.

Industry produces more than 4 trillion cubic feet of hydrogen annually, mostly by steam reforming natural gas or naptha products (in petroleum refinery operations) to produce the lowest cost hydrogen. Carbon dioxide is also produced in the steam reforming process, but emission into the atmosphere can be readily avoided. Systems analysis has shown that the added cost of carbon dioxide sequestration processes at large central plants is competitive with the cost of other pollution abatement options.

A key strategic objective of the nearer-term Hydrogen R&D Program is to develop advanced, highly efficient reforming processes to produce hydrogen from natural gas, which can be used for distributed generation sites (refueling stations). These advanced processes offer the potential of lower capital cost and/or higher yields. Another key issue in wide-spread use of hydrogen is industry's ability to store large quantities of hydrogen to meet shifting demands. In the natural gas industry, the storage problem was resolved by using depleted wells and other bulk storage techniques. This enabled the natural gas market to grow significantly due to meeting fluctuations in seasonal demand through the management of stored reserves. For hydrogen to be successfully used in the energy marketplace, a similar type of storage capability must be developed.

Hydrogen Program Mission

The U.S. Department of Energy Hydrogen Research and Development Program conducts research and engineering development in the areas of hydrogen production, storage, and utilization, for the purpose of making hydrogen a cost-effective energy carrier for utility, buildings, and transportation applications. This is being accomplished by:

- Performing research projects that introduce renewable-based options to produce hydrogen and that decrease the cost of producing hydrogen from natural gas;
- Developing hydrogen-based electricity storage and generation systems that will enhance the use of distributed renewable-based utility systems;
- Demonstrating fueling systems for hydrogen vehicles in urban non-attainment areas;
- Developing and lowering the cost of technologies to produce hydrogen directly from sunlight and water;
- Supporting the introduction of safe and dependable hydrogen-based energy systems, including the development of codes and standards for hydrogen technologies.

Concurrent with the growing pressure to mitigate global warming, there has been an increased emphasis on hydrogen produced from non-fossil energy resources, most notably from renewable energy resources. A long-term strategic goal of the R&D Program is to produce cost-competitive hydrogen from renewable energy resources. Using biomass, solar, wind, and geothermal energy, hydrogen could be an inexhaustible, convenient gaseous fuel to replace natural gas and other fossil fuels. The use of hydrogen as a fuel produces water as the only emission and thereby minimizes any negative impact on the environment.

The transition to hydrogen as an energy carrier is limited in part by the lack of available efficient end-use technologies. The development of practical and efficient utilization technologies is a key program objective. The Hydrogen Program is collaborating with the Fuel Cell Program in the Office of Transportation Technologies to develop Proton Exchange Membrane (PEM) fuel cells that use hydrogen fuel to generate electricity. Large-scale fuel cells can improve the overall efficiency of electricity production, impacting the entire electric utility industry, while small-scale fuel cells can make the electric car a practical vehicle option with sufficient range and power to meet drivers' needs. Presently hydrogen is the only practical fuel for direct use in a fuel cell.

For each technology area currently supported by the R&D Program, this document identifies the strategic objectives, establishes a timeline to achieve critical milestones, and projects when a technology is expected to be ready for validation (and incorporation into a full system for hydrogen utilization). The anticipated characteristics of each technology being developed are also tabulated. The applications of interest include electric power generation (and co-generation), electric vehicles, buildings, and industrial energy needs.

Since the projects presented here are in the research and development phase, there are inherent development risks. In such high-risk endeavors, achievement of milestones is not guaranteed; therefore, some projects are expected to fail from a technological standpoint. Other projects, although considered technological successes, will fail because cost goals for commercialization cannot be achieved. As projects fail to achieve milestones, they will be phased out and other projects will replace them in order to improve the chances of successfully meeting the program goals.

As successful components or technologies move through the Program's development process, they are integrated with other components or technologies into systems ready for technology validation. Exhibit 1 illustrates the key stages that innovative hydrogen technology concepts pass as they advance toward market introduction. As components or technologies are successfully scaled up, they will be integrated into systems ready for technology validation. The technology validation phase will test the use of full hydrogen systems in practical applications. As the technologies are proven, in collaboration with industrial support and participation, they will be adopted in the marketplace. Another Program report entitled, "The Hydrogen Program, Technology Validation Plan," discusses this post-R&D process. It provides examples of anticipated typical niche markets and details how the R&D program and its technology products would provide the systems to meet market needs.

International R&D Leadership

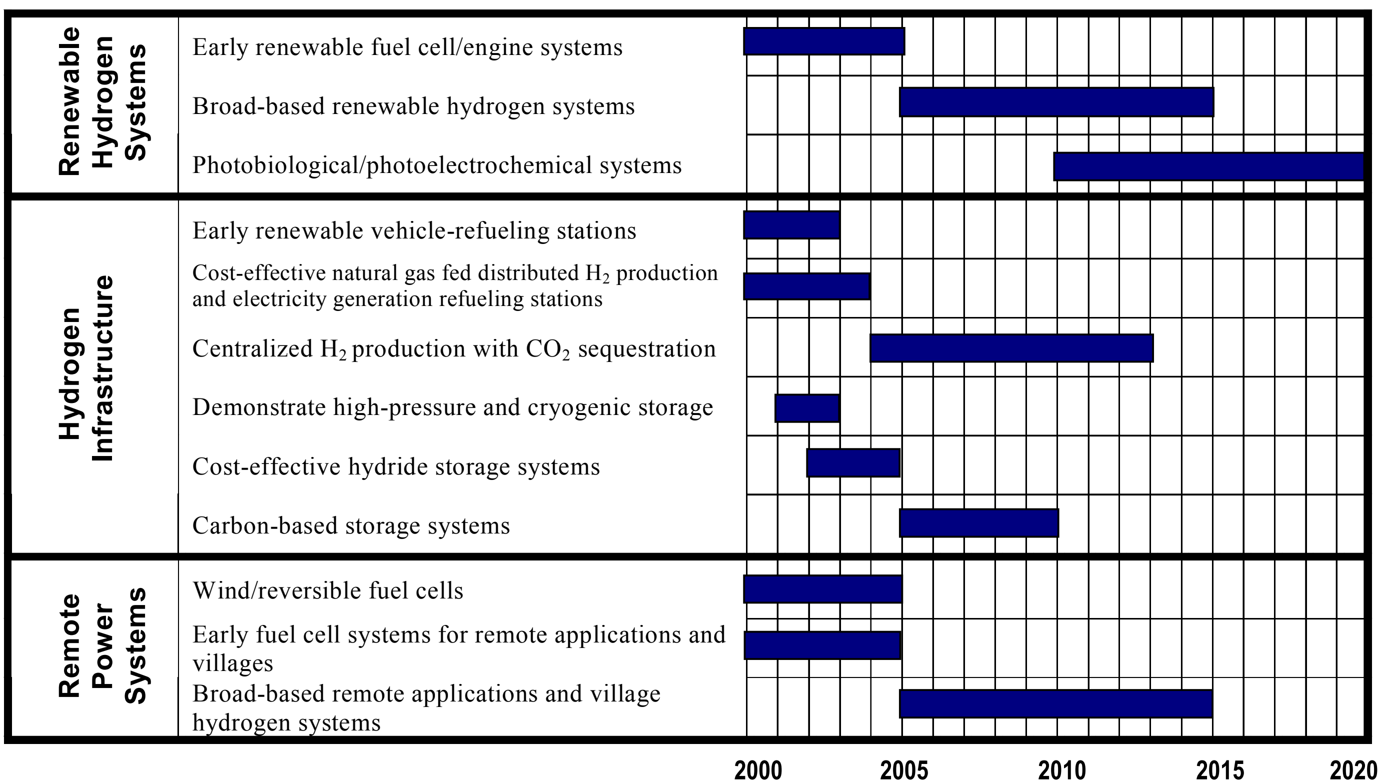
The DOE promotes international collaborations in hydrogen research and technology transfer through its participation in the International Energy Agency (IEA). The IEA, which is part of the Organization of Economic Cooperation and Development (OECD), was created to facilitate collaborations for the economic development, energy security, environmental protection, and well being of its members and of the world as a whole. The IEA is currently comprised of 24 member countries, 11 of which are active participants in the Hydrogen Implementing Agreement, focused on the utilization and productionofhydrogen. Twelve cooperative projects, including three ongoing activities in hydrogen production, storage, and integration, have been conducted since the IEA's establishment in 1977. The Hydrogen R&D Program has a prominent and active role in all three activities.

Exhibit 1: The Technology Development Process and Associated Stages

Core R&D	Component Research	Basic and applied research and material development using the fundamental sciences (e.g., biology, physics, chemistry) to enable and support the development of systems.
	Concept Development	Design and analysis of a basic subsystem that incorporates engineering design and analysis with a fundamental understanding of the science.
	Subsystem Engineering	Subsystem constructed: 10 % scale – commercial size. Subsystem combines the technology with auxiliaries. Design and test components scaling up the concept to 10% of commercial size with its auxiliaries.
Tech-nology	System Integration	Integration of several components, subsystems, and or systems into realistic test-beds.
	Prototype	Integration of sub-systems and systems into first-of-a-kind (FOAK) systems and prototypes.

The development of a fully integrated hydrogen energy economy will be a major societal accomplishment. Such an accomplishment will be the result of careful planning and analysis, fundamental and applied scientific research, engineering and systems integration, and industry and public outreach programs. Each year, significant technical milestones are achieved that move an emission-free energy system closer to reality. Exhibit 2 shows the timeline for the development of key hydrogen energy systems, many of which incorporate components under development within the Hydrogen Program.

Exhibit 2: Timeline for the Development of Key Hydrogen Energy Systems



2.0 Technology Overview

The Hydrogen Industry Today

Although there is currently no substantial use of hydrogen in commercial energy applications[1] in the U.S. and around the world, there does exist a mature hydrogen industry that serves various market niches. Total U.S. hydrogen consumption in 1997 was approximately 8.5 billion standard cubic feet per day (bscfd), with 40% dedicated to petroleum refining and 59% to chemical manufacturing. The remaining 1% is used in metal fabrication, oil and fat hydrogenation, rocket propulsion, and other small industrial markets. Exhibit 3 shows hydrogen consumption by application in 1997, as well as the industrial sector that supplied the hydrogen for each application. U.S. hydrogen production is increasing at a rate of 5-10% per year.

Exhibit 3. U.S. Consumption of Hydrogen Produced in 1997 (millions of cubic feet)

Industrial Sector	Captive Production	Merchant Production		Total Production
	Gas	Gas	Liquid	
Chemicals and Petrochemicals				
Ammonia	1,250,000	0	0	1,250,000
Methanol	312,000	0	0	312,000
Other	220,000	50,000	9,000	279,000
Petroleum Refining	1,120,000	105,000	0	1,225,000
Electronics	0	500	5,000	5,500
Edible Fats and Oil	5,000	0	900	5,900
Float Glass	0	0	900	900
NASA	0	0	3,500	3,500
Metals	1,000	6,000	5,000	12,000
Public Utilities				
Generator Cooling	0	260	0	260
Corrosion Prevention	20	60	170	250
Other				
TOTAL	2,908,020	161,820	24,770	3,094,610

The largest volumes of hydrogen are produced at the consumer's point of use. Petroleum refineries currently produce and use around 1200 bscf of hydrogen per year. Much of the hydrogen is produced by natural gas reforming and is used in various processes that include the desulfurization and upgrade of heavy oils, the generation of process heat (mixed with natural gas and combusted), and the refining of petrochemical products. An additional 1500 bscf is produced by the chemical industry largely for ammonia and methanol production.

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[1] Other than space applications. The NASA Space Shuttle uses hydrogen fuel to power rocket engines and fuel cells that generate electricity in space to satisfy all mission-related electrical demands.

Another segment of the hydrogen production industry serves the merchant hydrogen market. Merchant hydrogen refers to hydrogen produced and sold by industrial gas companies to small volume consumers. Merchant hydrogen, delivered in either gaseous or liquid form via cylinders, tank trucks, railcars or pipeline, is the primary source of hydrogen to industries such as electronics, glass and chemicals, and for specific applications (e.g., rocket fuels). Merchant hydrogen is also used to supplement the requirements of the captive producers. Although the merchant hydrogen market is the smallest portion of the total hydrogen business (at between 6-9% of the total hydrogen demand) it is also the fastest growing segment of the hydrogen market; growing at an average annual rate of 12 -17%.[2]

To meet the growing demand for hydrogen, additional production plants will have to be built or the capacity of current plants increased. This should encourage industry to consider the emerging, efficient production technologies, such as the advanced natural gas reforming technologies, sorbent enhanced reforming (SER), and partial oxidation (POX). In those markets with inexpensive electricity, little natural gas infrastructure, or where small volumes of high purity hydrogen are needed, water electrolysis is the preferred production technology.

2 Information based on Department of Labor statistics.

3.0 Roadmap Organization

The DOE Hydrogen Program consists of a diverse portfolio of projects at varying levels of development. Roadmaps have been developed to track the current status, set the course for future work, and identify critical decision points and milestones for each project. To evaluate project viability and to bridge from one status classification to the next, a matrix of technical, economic, and programmatic screens have been developed. Researchers, in cooperation with program managers, establish multi-year plans that include decision points and milestones as measures of success. Exhibit 4 lists the technical, economic, and programmatic criteria that bridge the research and validation activities.

Subsystems Engineering (SE) is the phase where subsystems at 10% commercial scale will be constructed and tested. Projects that meet technical milestones and prove successful in the laboratory scale-up and sub-system engineering phase of research will advance to the Technology Validation (TV) phase of the Program. This combination of research stages along with programmatic screens and review ensures successful development of the critical technologies for introducing hydrogen in the nation's energy mix.

Exhibit 4: Bridging the Span between Research and Validation

Bridges	Technical	Economic	Programmatic
Component Research to Concept Development	Projected environmental benefits Projected efficiency International collaboration	Projected costs based on inputs	Portfolio balance (near-, mid-, long-term; renewable, fossil-based)
Concept Development to Subsystem Engineering	Above + Lifetimes, durability Engineering complexity	Economic assessment based on preliminary design of system	Above + Industrial participation minimum 25% cost share. Participation of other DOE programs
Subsystem Engineering to Technology Validation	Above + Proof of concept Success of scale up experimental runs	Detailed economic assessment of life-cycle costs Comparison to existing or competitive processes Industry cost share	Above + Industrial participation, minimum 50% cost share State and local support

Specific Roadmaps for Hydrogen Technology Areas

Roadmaps have been developed for each of the three technology areas in the DOE Hydrogen Program. A short status report is given for each area to familiarize the reader with the technology, research needs, and important issues for commercialization of the technology. Exhibit 5 lists the current technology development activities of the DOE Hydrogen Program, as categorized in the following three focus areas: production, storage (including transport and distribution), and utilization.

Exhibit 5: Hydrogen Program R&D Technology Development Summary

Technology	Unit Operations
PRODUCTION TECHNOLOGIES	
Thermal Production Processes	
From Fossil Fuels Resources	
Sorbent Enhanced Reforming Of Natural Gas	Adsorbent development. Analysis of process schemes to optimize T, P, and recycle times.
Thermocatalytic Cracking Of Natural Gas	Catalyst identification, development, and optimization; carbon separation.
From Biomass Resources	
Biomass Gasification	Commercial-scale demonstration of indirectly heated gasifiers for power and syngas production; improvement in crop yields; reactor design to minimize alkali slag.
Slurry-Fed MSW Gasification	Pilot-scale demonstration of an MSW water-based slurrying process; development of a gasifier design optimized for MSW slurry feedstock.
Pyrolysis Of Biomass and MSW With Co-Product	Catalyst development for reforming of pyrolysis reactor effluent; testing of reforming catalyst de-coking procedures.
Electrolytic Production Processes	
Solid Polymer Electrolyte Electrolysis	Researching methods to reduce noble catalyst loadings.
High Temperature Steam Electrolysis	Developing materials capable of high temperature operation.
HBr Electrolysis	Laboratory-scale integration and testing of a reversible HBr cell.
Photoelectrochemical Processes	Development and optimization of PV materials for water splitting; development of tandem PV cells and oxidation and reduction catalysts.
Photobiological Production Processes	
Photobiological Processes	Selection and development of hydrogen-producing species (bacteria and algae); molecular engineering of organisms and process development; extraction of the hydrogen producing catalysts (enzymes).
STORAGE TECHNOLOGIES	
Physical Storage	
Advanced High Pressure Gas Container Systems	Materials development, optimization of carbon fiber wrapping, pressure vessel stresses and failure analysis
Chemical Storage	
Carbon Adsorption	Low temperature (active cooling), Impurities, Low volumetric energy density
Metal Hydrides	Poisoning of alloy by impurities, Heat management, Weight and volume, Low cost alloys and containers
Catalyzed Hydrides	Optimization of catalysts and hydride materials, safety studies, and analysis of the effect of impurities. Conduct engineering analysis into system requirements and manufacturing needs.
Polyhydrides	Optimization of binary aluminate compounds for use as catalysts, and development of synthesis methods and processes capable of production scale-up.
UTILIZATION TECHNOLOGIES	
Electrochemical Utilization Processes	
Proton Exchange Membrane Fuel Cell*	Investigation of lower cost components for membrane assemblies, catalyst poisoning (CO), and stack design
Combustion Utilization Processes	
Internal Combustion Engine*	Efficient Mixing, Flashback, No_x Emissions
Hydrogen Detection	
Chemochromic Fiber Optic and Thick Film Sensors*	Optimization of system kinetics and selectivity, and research into the poisoning of chemochromic catalyst and thick film materials.

4.0 Hydrogen Research and Development Overview

Examination of the various pathways to produce, store, and utilize hydrogen suggests that with certain technology advances, hydrogen can become an economically viable energy option. The R&D Program focuses on the advancement of these technologies. The Hydrogen Program has developed collaborations with other offices within the Department and with other Implementing Agreements within the International Energy Agency (IEA) to co-fund and co-manage projects in the following critical technologies:

- direct photoconversion production using photobiological and photoelectrochemical methods
- fossil fuel reforming technologies for small distributed production systems
- biomass growth, harvesting and conversion
- coal gasification, hydrogen purification and carbon dioxide sequestration
- fuel cells for stationary, appliance, and transportation applications
- efficient, safe, low-cost storage systems for stationary and mobile applications
- catalytic and heat engine conversions

As research and development activities progress, industry is encouraged to work with the research teams through cooperative agreements and CRADAS to both validate and evaluate the evolving technologies that will enable implementation of hydrogen energy systems.

IEA Implementation Programs

The Hydrogen Implementing Agreement has also established ties with several other IEA programs, including those in renewables and the Greenhouse Gas (GHG) R&D Program. The GHG Program was established to evaluate the technical and economic feasibility and the environmental impacts of technologies for the abatement, control, utilization, and disposal of carbon dioxide and other greenhouse gases resulting from fossil fuel use. The GHG Program investigates energy markets and economic impacts of the implementation of potential abatement options.

A related IEA activity is the recently formed Climate Technology Initiative (CTI). The CTI is designed to promote national and international policies that can improve the framework for science and technology delivery systems. It will contribute to meeting climate change objectives with the lowest possible cost by improving the rate of technological development and deployment. This will be achieved through the demonstration of new and improved technologies, and through national and international efforts by governments and industries, to strengthen technological progress.

4.1 Hydrogen Production Technologies

Strategic Objectives:	**Develop processes to produce hydrogen from fossil fuels, biomass, and renewable energy sources to meet both central and distributed production goals.**

Production Goals:	**\$6-8 per million Btus for fossil based technologies** **\$6-8 per million Btus for biomass based technologies** **\$10-15 per million Btus for photolytic based technologies** **50% bioconversion and/or 15% photoconversion efficiency**

The DOE Hydrogen Program has established the above production cost and conversion efficiency goals for hydrogen production research. Technologies under investigation are expected to compete economically with available technologies or are required to demonstrate commensurate environmental benefits. The niche market applications, where convenience, reliability, energy security, or environmental issues may outweigh cost issues, are considered prime targets for initial implementation of advanced production processes.

Current hydrogen production processes are based on the thermal conversion of fossil fuels, or the electrolysis of water. Process improvements that reduce the cost of production and new technologies that offer environmental and/or cost benefits are the subject of these research efforts. Hydrogen can also be directly produced by splitting water molecules with sunlight catalyzed by biological organisms or semiconductor-based systems similar to photovoltaics. All renewable resources are ultimately derived from the sun; therefore, other renewable-based hydrogen production systems include PV/electrolysis, wind/electrolysis, and thermal conversion of biomass. These production technologies have the potential to produce essentially unlimited quantities of hydrogen in a sustainable manner. Exhibit 6 lists the hydrogen production technologies that have been considered by the program and their current development status.

Thermal Processes

Thermal processes use heat to convert carbonaceous feeds such as natural gas, naphthas, coal, biomass, and municipal solid waste (MSW) into hydrogen and carbon dioxide. By optimizing the various operating parameters, hydrogen produced from thermal processes can be improved by as much as a factor of five. The Program's research objectives are to improve the hydrogen yield from these processes, to reduce production costs, and to minimize release of atmospheric pollutants. For the long-term, emphasis is placed on improving hydrogen production capabilities using non-fossil resources such as sustainable biomass.

Exhibit 6 -- Hydrogen Production Technologies

Hydrogen Production Technology	Development Status	Key Research Areas	Validation
Hydrogen Production From Fossil Fuels			
Steam Reforming Of Natural Gas	Commercial	Incremental improvements in heat integration and catalyst life	This technology is commercial and not included in the Hydrogen Program R&D effort.
Catalytic Reforming Of Light Hydrocarbons	Commercial	Coking problems, cost of platinum catalyst.	This technology is commercial and not included in the Hydrogen Program R&D effort.
Coal Gasification	Concept Development, Systems Engineering	Pre-commercial demonstrations for power and syngas production. Performance improvement and cost reduction of high temperature membranes for SO_2 and particulate removal from syngas.	Based on economic and environmental analysis, this technology does not meet the portfolio requirements of the Hydrogen Program R&D effort.
Partial Oxidation Of Fossil Fuels And Biomass	Commercial, Concept Development	Reduced capital cost of gasifier and oxygen plant.	--
Sorbent Enhanced Reforming Of Natural Gas	Component Research, Concept Development, Systems Engineering	Pilot-scale development of a process that drives the reforming reaction via a CO_2 adsorbent.	2001
Plasma Reforming Of Fossil Fuels And Biomass	Component Research, Concept Development, Systems Engineering	Design and optimization of integrated plasma reforming system for liquid fuels.	2002
Thermocatalytic Cracking Of Natural Gas	Component Research	Catalyst identification and optimization, carbon deposition.	2003
Ion Transport Membranes To Produce H2 From Natural Gas	Component Research, Concept Development, Systems Engineering	Awaiting information.	2003
Hydrogen Production From Biomass			
Slurry-Fed MSW Gasification	Component Research, Concept Development	Pilot-scale demonstration of an MSW water-based slurrying process; development of a gasifier design optimized for MSW slurry feedstock.	2003
Supercritical Biomass Gasification	Systems Engineering	Commercial-scale demonstration of indirectly heated gasifiers for power and syngas production; improvement in crop yields; reactor design to minimize alkali slag.	2003
Pyrolysis Of Biomass And MSW With Co-Product	Component Research, Concept Development	Laboratory-scale development of catalyst for reforming of pyrolysis reactor effluent; testing of reforming catalyst de-coking procedures.	2003
Electrolytic Production Processes			
Alkaline Electrolysis	Commercial	Pilot/commercial-scale testing of non-asbestos diaphragm materials; development of electrode materials with reduced overpotentials.	This technology is commercial and not included in the Hydrogen Program R&D effort.
High Temperature Steam Electrolysis	Component Research,	Laboratory-scale research into high temperature materials.	2003
Photoelectrochemical Processes	Component Research, Concept Development	Optimization of PV materials for water splitting; laboratory-scale development of tandem PV cells and oxidation and reduction catalyst development.	2003
HBr Electrolysis	Concept Development, Systems Engineering	Laboratory-scale development and integration of an HBr electrolyzer and a reversible fuel cell.	2000
Solid Polymer Electrolyte Electrolysis	Concept Development	Laboratory-scale research into reduced noble catalyst loadings.	2003
Photobiological Production Processes			
Bacterial Water Gas Shift Reactions	Component Research, Concept Development	Laboratory-scale isolation of hydrogen-producing species (bacteria); development of a bioreactor design that enhances mass transfer	2002
Algal Systems For The Separation Of Water	Component Research, Concept Development	Laboratory-scale isolation of hydrogen-producing species (algae); strain improvement and process development.	2003

Fossil Fuel-Based Hydrogen Production

Sorption Enhanced Reforming of Natural Gas

The goal of this project is to demonstrate the feasibility of producing hydrogen via low-temperature steam methane reforming in a novel process using simultaneous reaction of methane and adsorption of CO_2. In contrast to the commercial steam methane reforming (SMR) process, Sorption Enhanced Reforming (SER) will operate at a significantly lower temperature by shifting the equilibrium in favor of hydrogen production through selective removal of CO_2 from the reforming step. The process is designed to produce a high purity hydrogen stream and a high purity CO_2 stream, without the need for an expensive purification subsystem such as pressure swing adsorption. The economic potential of the SER process could be significant given the reduced capital and operating costs of the process. In addition, the interest in reducing atmospheric concentrations of greenhouse gases such as CO_2 could favor the SER process over conventional processes. Since a significant portion of the current hydrogen production volume comes from conventional SMR, the enhancements to the economic and environmental aspects of hydrogen production using the SER process could impact the transition to a hydrogen economy in the near term.

DOE is supporting Air Products and Chemicals (Allentown, PA) in the development of the SER process. Key research areas include identification of suitable adsorbents (capacity, stability, kinetics), demonstration of the technical feasibility of a single-step experimental apparatus, and estimation of the economic benefits. The project will design, install, and operate a full-scale process development unit (PDU) to demonstrate performance of this process by FY 2000 and will scale-up the process for commercial operation in FY 2001.

Hydrogen Production from Sorption Enhanced Reforming of Natural Gas

Technology Validation			Two scaled (10%) reactors.						Scale-up process for Commercial Operation.		
								3			
Subsystem Engineering	Complete design of a PDU for the sorbent process.		Fabricate and install 2-column lab PDU at the Allentown Air Products plant laboratory.		Develop design for full-scale PDU using sub-scale 2-column unit.		Install and operate the PDU to demonstrate performance of process.				
				2							
Concept Development			Develop operating parameters for the process.				Complete economic evaluation of process.				
		1									
Component Research	Select candidate materials for scale-up.										
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Absorbent must achieve repeated thermal cycles.

2 Decision Point: Achieve 20% reduction in thermal energy for conversion.

3 Decision Point: Economics shall achieve 15% reduction in cost.

Hydrogen Manufacturing using Plasma Reformers

The goal of this project is to develop an economic and compact plasma reformer for the production of hydrogen from hydrocarbons. Plasma is a highly energetic state of matter characterized by high temperatures and large amounts of ionization. Plasma reformers offer several advantages over conventional processes, including high power density, fuel flexibility, fast response time, simple materials of construction, and high conversion efficiencies. The plasma reformer can be operated in a variety of process configurations, including partial oxidation, steam reforming, and pyrolysis. Researchers are examining the thermal decomposition process to determine whether emissions of CO and CO_2 can be eliminated. In addition, work focuses on the design of a compact reactor to incorporate the reforming and water gas shift reactions in one stage.

DOE is supporting the Massachusetts Institute of Technology (Cambridge, MA) in the development of compact plasma reformers for utility and transportation applications. Key research areas include identification of optimum system configurations characterized by low energy consumption, high hydrogen yield, short response time, and high power density. The project will include the design of an integrated plasma reforming system using liquid fuels that will be built and operated in FY 2000. Goals for the operation of this prototype system are 5-7 kW (electrical input), 80-100 kW H_2 product, thermal equivalent. The system will be scaled up by FY 2001 to permit system operation at 30 kW (electrical), 250-300 kW H_2 equivalent. This will be followed by lifetime testing, plasmatron optimization, and transfer of the technology to industry in FY 2002.

Hydrogen Production from Natural Gas via Plasma Reforming

Technology Validation									Operation of plasmatron system up to 30 kW (electric) 250-300 kW H2 equivalent.		Technology transfer. Lifetime testing. Plasmatron optimization.
								2		3	
Subsystem Engineering					Design integrated process system for liquid fuels.		Fabricate integrated plasma reformer. Operations of plasmatron system up to 5-7 kW (electric), 80-100kW H2 equivalent.				
Concept Development	Test Plasmatron Concepts using natural gas.		Calculate material and energy balances for plasmatron process.		Test Optimum System using natural gas.		Finalize economics based on experimental results.				
				1							
Component Research	Scale-up Design.		Optimize Design.								
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Decrease energy consumption by 25%.

2 Decision Point: Complete economic evaluation to demonstrate process can produce hydrogen at prices conventional processes.

3 Decision Point: Identify Industrial Partner for Technology Transfer.

Thermocatalytic Cracking of Natural Gas

The goal of this project is to develop a single-step hydrocarbon decomposition process for the CO_2-free production of hydrogen. In comparison to conventional technologies, thermocatalytic decomposition of hydrocarbons in the absence of air or oxygen would avoid the expensive gas separation unit that is required for the SMR and partial oxidation processes, and it would not result in the production of carbon monoxide or carbon dioxide. The research is currently focused on identification and modification of appropriate carbon-based catalysts for the process; and the design, fabrication, and testing of a laboratory-scale reactor. Once catalysts are identified, the process will be optimized for high hydrogen yield.

DOE is supporting the Florida Solar Energy Center (Cocoa, FL) in the development of a thermocatalytic hydrogen production process that operates on liquid and gaseous hydrocarbon fuels. Key research areas include the identification of stable and effective carbon-based catalysts, testing of various carbonaceous fuels, and optimization for hydrogen yield. Between FY 2000 and FY 2003, several hydrocarbon fuel processors will be designed and constructed. These units will consist of a 1 kW bench-scale unit, 5 kW pilot scale processor, and 25-50kW prototype. Fuel processor systems will be engineered to optimize hydrogen yield (purity) and eliminate the emission of carbon monoxide and carbon dioxide. The project goals for the fuel processor system are to achieve hydrogen yield of greater than 85%, and carbon monoxide emissions not to exceed 100 ppm during FY 2001. During FY 2002, the pilot scale fuel processor will be tested in combination with a fuel cell unit capable of a 5 kW power output.

Hydrogen Production from Hydrocarbon Fuel Processor using Thermocatalytic Cracking

Technology Validation									Fabrication and testing of a pilot scale fuel processor in combination with fuel cell (5kW).		Construction and testing of a prototype fuel processor (25-50kW).
								3		3	
Subsystem Engineering			Design and construction of a bench scale processor (1 kW).		System engineering to optimize H2 yield and further reduce [CO], [CO2].		Production of Hydrogen-rich gas (>85%) with [CO]<100 ppm.		Testing of the pilot scale fuel processor in combination with fuel cell (5kW).		Hydrocarbon fuel processor control and safety systems.
				1		2					
Concept Development	Process feasibility studies. Laboratory scale unit (0.1kW).		Processing of gaseous and liquid hydrocarbons to hydrogen with purity of 70-80 V%.		Processing of Natural gas and gasoline to hydrogen with purity of 80 v% and [CO], 0.1v%.		Process Engineering. Reactor modeling. Continuous removal of carbon from the reactor.		System integration analysis. Energy analysis of the fuel processor.		
Component Research	Search for active catalysts and optimum process conditions.		Selection of effective and stable carbon and metal-catalysts.		Solution of carbon problem. Long term stability of catalysts.		Processor construction materials compatibility test.				
Year	1997		1999		2000		2001		2002		2003

1 Decision Point: Must process model gaseous and liquid hydrocarbons to hydrogen-rich gas ([H2] = 70-80v. %).

2 Decision Point: Must process gasoline to hydrogen with purity of 80 v. % and higher and [CO] and [CO2], 0.1 v. %.

3 Decision Point: Must process gasoline and natural gas hydrogen with purity of 85 v. % and [CO]< 100ppmv, suitable for PEM fuel Cell applications.

Ion Transport Membrane

The goal of this proposed project is to develop the ion transport membrane (ITM) technology for the manufacture of syngas (carbon monoxide and hydrogen) from natural gas at 30-50% of conventional production costs. This research and development project will focus on the use of conducting ceramic membranes to separate oxygen from air while simultaneously converting natural gas to hydrogen. Air is preheated to over 600^{o}C and passed through an ITM reactor at pressures up to 600 psig. The reactor is composed of a non-porous ceramic membrane that selectively transports oxygen through the crystal lattice. The oxygen reacts with a catalyzed wall on the fuel side and then passes through a reforming catalyst bed to produce the syngas.

Both the Hydrogen Program and the Gas to Liquids Program elements of the DOE are supporting Air Products and Chemicals in the development of the ceramic materials, integration and manufacturing of the membranes, and development of the balance of the production system (including the purification). Key research areas include ceramic materials development, development of tubular membranes, ITM syngas reactor designs, high temperature seals, and operation of process development units. The project will result in the design, installation, and operation of subsystem components for a syngas reactor utilizing the ITM technology. This technology will be tested and evaluated during the FY 2000 to FY 2001 time frame, while the technologies and subsystems will be readied for a FY 2002 pre-commercial demonstration of the ITM syngas reactor designs.

Hydrogen Production from Natural Gas via Ion Transport Membrane Technology

Technology Validation									Precommercial Demonstration Planning.		
Subsystem Engineering					Engineering Development.		Engineering Development and Testing.		Subsystem Testing and Evaluation.		
								2			
Concept Development			Process Definition and Cost Trades.		Process Design of Syngas Reactor.		Membrane System Fabrication.				
				1							
Component Research	Materials and Seals Development.		Materials and Seals Development.		Material Selection.						
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Must achieve 50% of target performance.

2 Decision Point: Must achieve 80% conversion.

Biomass-Based Hydrogen Production

Slurry-fed MSW Gasification

The goal of this project was to develop an environmentally advantageous gasification process for the production of hydrogen from municipal solid waste (MSW), plastic waste, and other low-value feedstocks. Conventional thermal treatment of waste streams often results in an ash or solid waste stream that contains heavy metals and other contaminants, and requires costly disposal as a hazardous waste. A commercially available slagging gasifier was used to produce hydrogen without the hazardous solid waste disposal problem typical of processes using these mixed wastes. The byproduct of the process would be a vitrified or "glassy" ash that would not require special disposal. The feeds required pretreatment to be suitable for injection into the slagging gasifier. In particular, the energy content of the slurried waste had to be above a minimum value to sustain the gasification reaction. Since MSW is 70% paper (on average) and paper can contain significant quantities of moisture without acting as a slurry, thermal pretreatment options and the use of additives were under consideration.

DOE supported Lawrence Livermore National Laboratory (LLNL, Livermore, CA) in the development of a cost-effective feedstock-preprocessing unit to prepare the mixed wastes for injection into the Texaco slagging gasifier. Texaco and LLNL had a CRADA (Cooperative Research and Development Agreement) for this effort, with LLNL developing the pretreatment process and Texaco concentrating on the operation of the gasifier. Key research areas included development of an efficient and cost-effective pretreatment process for waste feedstocks. As a result of detailed process evaluation, this project was suspended because it did not meet the cost targets of the Program.

Hydrogen Production via Slurry-fed MSW Gasification

Technology Validation					Design and construct 10-ton/day integrated pilot plant w/ industry.		Shakedown of pilot plant.		Run plant using test matrix of different feedstocks.		
Subsystem Engineering			Operate gasifier pilot plant.								
			Project suspended—see text.								
Concept Development			50% H2 production efficiency on a 1-ton/day scale. Produce two 1-ton slurry batches.								
		1									
Component Research	Pretreatment process evaluation.		Demonstrate non-leaching character of ash.								
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Pretreatment process must prove to be technically and economically viable.

NOTE – Decision point 1 was not met and further work on this project was discontinued.

Supercritical Gasification of Biomass

The goal of this project is to develop a supercritical water biomass gasification process for production of hydrogen from high moisture feeds. Biomass contains, on average, about 50% water, and most thermal processes require significant reduction of the moisture content for efficient operation of the gasification or pyrolysis process. The supercritical water gasification process would eliminate the need for dryers, and would enable the use of a wider variety of feeds. Biomass slurries injected into a supercritical steam-reforming reactor are converted into H_2 at high pressure. The high heating rates, in conjunction with novel carbon catalysts, suppress the formation of tars and char, and achieve complete reforming of the biomass. Slurry preparation and delivery, catalyst development, and reactor optimization are key research areas for the development of this process.

DOE is supporting Hawaii Natural Energy Institute (HNEI/University of Hawaii, Honolulu, HI) and Combustion Systems, Inc. (Silver Spring, MD) in the development of a practical, efficient, and cost-effective process for the production of hydrogen from high moisture content biomass in supercritical water. Key research areas include development of a slurry delivery system and the identification and optimization of appropriate catalysts. The project will result in the design, fabrication, and operation of a reactor system capable of gasifying biomass to produce hydrogen. The first reactor system will be fabricated during the 1999 fiscal year. During FY 2000, this reactor system will be scaled-up to a one-inch diameter reactor chamber with internal heating. Testing, data acquisition, and system analyses for this technology will be completed during the 2001 fiscal year, and it is anticipated that the technology will be transferred to industry during the following fiscal year.

Hydrogen Production via the Supercritical Gasification of Biomass

Technology Validation									Open negotiations on license.		Transfer data and system to industry.
Subsystem Engineering					Design heater system for the process and balance of system.		Operate reactor system.		Operate and collect data.		
						2		3			
Concept Development			Design high-pressure reactor for varying residence time, temperature and mixing length. Determine ash and product gas composition.		Fabricate reactor system. Calculate nitrogen balance around the reactor. Calculate heat demands. Determine the reactor wall's role as catalyst.		Scale-up reactor to 1 inch diameter with internal heating. Develop new feeder concept.		Complete economic assessment including sensitivity analysis of process.		
		1									
Component Research			Develop optimal biomass feed including heating value, solids concentration, viscosity, and starch.		Determine effects on carbon catalyst.						
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Reduce 40% by weight slurry with pumpable viscosity. 2 Decision Point: Convert 90% of the feedstock with out any carbon build-up.

3 Decision Point: Validate economics. Can be achieved using accumulated data.

Pyrolysis of Biomass with Co-Product

The goal of this project is to develop a biomass conversion process suitable for regional small-scale conversion of diverse biomass resources and conversion of the resulting liquid in a central facility into hydrogen and co-products. Agricultural wastes, forest residues, and dedicated biomass feedstocks are likely to be available in relatively small quantities over a wide area. Since transporting biomass is relatively energy-intensive due to the low energy density of the material, it is advantageous to thermally convert the solid feeds into a liquid "bio-oil" via pyrolysis near the point of collection. The resulting liquid is more cost-effective and easier to transport to a central processing facility for hydrogen and co-product conversion. A number of small-scale pyrolysis units would supply bio-oil to a single processing facility. Advanced pyrolysis technologies are needed to optimize the production of bio-oil with the appropriate chemical composition for maximum income generation. The production of hydrogen from specific fractions of the bio-oil requires a catalytic steam reforming process similar to that used in the commercial SMR process. Reactor configuration, catalyst formulation, and system operating parameters have a significant effect on losses associated with the thermal decomposition of biomass liquids to solid carbonaceous deposits that occur during steam reforming. In addition, a wide variety of co-products could be produced from the bio-oil to improve the process economics. Selection of the co-products would be dependent on market forces.

DOE is supporting National Renewable Energy Laboratory (NREL, Golden, CO) and the Jet Propulsion Laboratory (JPL, Pasadena, CA) in the development of a hydrogen production process via small-scale biomass pyrolysis units and a centralized bio-oil processing plant that is practical, efficient, and cost-effective. Key research areas include the development of an appropriate catalytic reforming technology for specific bio-oil fractions and the identification of valuable co-product strategies. The project will result in the design, construction, and operation of a process development unit (PDU), between FY 1999 and FY 2002. The operation of the PDU will provide the opportunity for critical lifetime testing of the PDU system and yield data from over 1000 total hours of operation. During FY 2002, this PDU will be optimized based on the data analysis from the PDU testing. This technology will be validated with industry during the 2003 fiscal year with the construction and operation of an "early development unit."

Hydrogen Production via the Pyrolysis of Biomass with Co-Product

Technology Validation													Construct and commission EDU with industry.
												2	
Subsystem Engineering							Design and construct PDU.		Commission PDU		Operate PDU for >1000 hrs		Optimize PDU
				1									
Concept Development	Bench scale activities: 80-90% of stoichiometric yield in fixed bed. Catalyst regeneration in fixed bed.		Bench scale activities: Maintain catalyst activity >8 hrs w/ 80% yield in fluid bed. Reform whole pyrolysis oil in fluid bed. Reform hemicellulose fraction in fluid bed.		Lifetime testing >24 hrs and 80% yield.		Lifetime testing >100 hrs and 80% yield.		Lifetime testing >300 hrs and 80% yield.				
Component Research	Catalyst development		Catalyst development		Catalyst development								
Year	1997		1998		1999		2000		2001		2002		2003

1 Decision Point: Must maintain catalyst activity and reform both the whole oil and the hemicellulose fraction before design and construction of PDU.

2 Decision Point: Must optimize the operation of the PDU and identify industrial partner prior to EDU work.

Electrolytic Processes

Electrolytic processes encompass all production activities based on the formation of hydrogen from water via electric current. Electrolysis of water is a common commercial process for on-site small-scale production of high purity hydrogen. Alkaline water electrolyzers are commercially available for this application, and research continues on the development of halogen electrolyzers and proton exchange membrane (PEM) electrolyzers. Photolytic processes using solar energy to drive the water splitting reaction are the subject of intensive research. In photoelectrochemical processes, semiconductor materials similar to photovoltaics are used to harness solar energy for direct water splitting. There are two types of photoelectrochemical systems; one using semiconductors and the other using dissolved metal complexes.

In the first type, a semiconductor surface is used to both absorb solar energy and act as an electrode for splitting water. This technology is still at an early stage of development, although energy conversion efficiency has increased from less than 1% in 1974 to more than 8% at present. Even higher efficiencies have been obtained with the addition of an external electric charge to help drive the chemical reaction.

Operating lifetimes of these systems are limited because of the light-induced corrosion of semiconductor materials and other chemical effects. Current research is focused on improving cell energy conversion efficiency and lifetimes, and reducing costs.

Advanced Electrolysis

High Temperature Steam Electrolysis

Research into high-temperature steam electrolysis (HTSE) technologies offers the opportunity to reduce electricity consumption associated with hydrogen production to an estimated 35% of that used by state-of-the-art, commercially available electrolyzer systems. As a result, hydrogen production from HTSE will be cost competitive with steam reforming, with much lower investment in capital equipment. In addition to its use for industrial-scale hydrogen production, the Lawrence Livermore National Laboratory (LLNL, Livermore, CA) electrolyzer concept represents a potential breakthrough in distributed hydrogen production for local hydrogen refueling stations and on-board hydrogen generators.

High temperature (900-1000 C) water electrolysis has the advantage of both electricity and heat supplying the required reaction energy. The high temperature of the system accelerates the reaction kinetics, reducing the energy loss due to electrode polarization and increasing the overall system efficiency. The proposed LLNL system increases the energy efficiency of the high temperature steam electrolyzer process using novel chemical and electrochemical concepts, and advanced materials. The principal efficiency gain is realized by minimizing the open-circuit voltage against which the steam electrolyzer is forced to operate. In addition, unique concepts are used to enhance hydrogen production while minimizing electricity consumption. This technology concept will make possible the use of a planar system design. The planar system is known in solid oxide fuel cell research to be much more compact and to yield higher power density than the typical tubular set-up. Thin film deposition technology developed at LLNL will be used to deposit the electrode/electrolyte materials.
Electrical consumption required to produce hydrogen is estimated at about 0.3 kWh/m^3 H_2 (standard

state) for a steam electrolyzer functioning at 900°C and at atmospheric pressure. The electrolyzer efficiency (with respect to primary energy) has been estimated to be in the range of 88-95%, compared to steam reforming efficiency of 65-75%. The initial first cost of the systems will be roughly equivalent, but the modularity and size flexibility of the LLNL system will make distributed hydrogen generation possible. The project will result in the design and construction of a prototype 1 kW high temperature and high-pressure Beta test unit during the 2003 fiscal year. Prior to the scale-up of the prototype 1 kW systems, the project will progress through several stages of development, including 10W, 100W, and 1kW stack units for testing and evaluation. Throughout the development period of this system, industrial partnerships will be sought and selected as criteria for the construction and operation of the Beta test pre-commercial units. Patent applications on the LLNL technology have been filed.

Hydrogen Production from High Temperature Steam Electrolysis

Technology Validation			Select industrial partner for commercial pre-prototype validation / obtain co-funding commitment.		Select industrial partner for commercial pre-prototype validation / obtain co-funding commitment.				1 kW Beta test unit (low-pressure operation).		1 kW Beta test unit (high-pressure operation).
								5		6	
Subsystem Engineering			1. System design for 100 W stack with small, integrated water shift reactor. 2. Start fabrication of large area thin film deposition equipment.		1. System design for 1 kW stacks. 2. Complete fabrication of large area thin film deposition equipment.		Design high-pressure system (higher efficiency).				
Concept Development	Evaluation of utility by systems analysis.				Updated systems analysis.		Evaluate high-pressure operation efficiency improvements.				
		1		2		3		4			
Component Research	Single cell fabrication and evaluation.		1. Construction and testing of 10 W stack. 2. Evaluate water-splitting catalysts.		Construction and testing of prototype 1 kW high-pressure system.		Construction and testing of prototype 1 kW high-pressure system.		Construction and testing of prototype 1 kW high-pressure system.		
Year	1998		1999		2000		2001		2002		2003

1 Decision Point: Demonstrate feasibility of approach with single cell (FY98).
2 Decision Point: Proof of principle for stack development (10 W) and demonstration (FY99).
3 Decision Point: Demonstration of lab-scale prototype system (100 W) with integrated shift reactor and comparison of system efficiency to alternative approaches to H2 production (FY00).
4 Decision Point: Laboratory demonstration of prototype 1 kW system with realistic potential for commercialization; evaluate potential for high-pressure operation efficiency improvements (FY01).
5 Decision Point: Beta test pre-commercial 1 kW low-pressure unit (FY02).
6 Decision Point: Beta test pre-commercial 1 kW high-pressure unit (FY03).

Reversible Hydrobromic Acid Electrolysis

The goal of this project is to develop an advanced, small-scale reforming technology that can produce low-cost hydrogen from natural gas and—when coupled to a reversible fuel cell—also provide energy storage. The electrical energy needed to electrolyze HBr is half of the potential to split water into hydrogen and oxygen. The challenge is to develop an efficient reactor with a minimum amount of tar formation. DOE is supporting SRT Group (Coconut Grove, FL) in the development of a quartz reactor that will be coupled to a National Power (United Kingdom) electrolysis system to demonstrate the integrated process. The project will design, fabricate, and validate an integrated 100 kW storage demonstration unit. Bench scale HBr electrolysis units and subsystems of 50 kW and 100 kW will be fabricated and tested during FY 1999 and FY 2000, respectively. Also in FY 2000, a 10 kW fully integrated HBr electrolysis hydrogen production unit with reversing capabilities will be designed for future scale-up into the 100 kW storage system.

Hydrogen Production in Reversible HBr Electrolysis

Technology Validation									Conduct 100 kW energy storage demonstration.		
								3			
Subsystem Engineering							Fabricate 100 kW bench-scale HBr electrolyzer sub-system.		Scale-up designs for a 100 kW integrated system with reversing capabilities.		
						2					
Concept Development					Fabricate 50 kW bench-scale HBr electrolyzer unit and test sub-system.		Design integrated 10 kW HBr electrolysis hydrogen production system with reversing capabilities to generate electricity during peak hours.				
				1							
Component Research			Design 50 kW HBr Electrolysis unit.								
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Approved National Power design for electrolysis unit.

2 Decision Point: Data collected to indicate, >40% round-trip efficiency.

3 Decision Point: Electrical performance of integrated system meets established cost goals.

Photoelectrolytic Production

Photoelectrochemical Production

The goal of this project is to develop a stable, cost-effective, photoelectrochemical based system that will directly split water into hydrogen and oxygen using sunlight as the only energy input. In contrast to a PV/electrolysis system, these monolithic devices will not require external wiring, converters, or other interface devices. For any direct conversion process to be viable, the light harvesting system must generate enough voltage to decompose water, and the system must be stable in a water environment. Researchers are using multijunction cell technology developed by the photovoltaics industry to develop these light-harvesting systems. Multijunction cell technology connects photovoltaic layers with different semiconductor bandgaps in a series, one behind the other, to produce a single cascade device. This configuration results in greater utilization of the solar spectrum, thereby providing the highest theoretical conversion efficiency for any photoconversion system. The cascade structure also minimizes the amount of active area needed. Amorphous silicon multijunction devices consist of multiple layers of a-Si cells and provide higher efficiency than single junction cells, in addition to reduced photodegradation that is common in all a-Si devices. Stability in an aqueous environment is a key research area for these low-cost systems.

DOE is supporting the National Renewable Energy Laboratory (NREL, Golden, CO) and the Hawaii Natural Energy Institute (HNEI)/University of Hawaii (Honolulu, HI) in the development of direct hydrogen production systems that are cost-effective, efficient, stable, and easy to manufacture. Key research areas include the extension of cell lifetimes, improving cell stability, and identification of cell configurations with high solar conversion efficiencies. This project will result in the design, construction, and operation of a robust product photoelectrochemical production system (PECPS) to directly convert solar energy to hydrogen. The first reactor system will be fabricated during the 2001 fiscal year. During FY 2002, a 20cm x 20cm bench scale system will be tested. Testing, data acquisition, and system analyses for this technology will be completed during FY 2003, after which the technology will be transferred to industry.

Photoelectrochemical Production of Hydrogen

Technology Validation													
Subsystem Engineering					Preliminary system design		System design		Build 20x20 cm^2 module (~4 W).		Operate 20x20 cm^2 module (indoor/ outdoor).		100 W prototype system (outdoor).
				1								3	
Concept Development			1000 hrs lifetime for protected cells immersed in electrolyte. >10% efficient III-V tandem cell.		3000-hrs lifetime for protected cells immersed in electrolyte.		6000-hrs lifetime for protected cells immersed in electrolyte.		>8% efficiency and >3000 hrs operation (bench).		3 month stability of tandem cell.		>8% efficiency and >3000 hrs operation.
										2			
Component Research	Surface treatment. Catalytic coating lifetime of 6000+ hours. 3 days operation of III-V tandem cell. 7.8% efficient a-Si cell.		Improved surface coating for a-Si cell. Cell configuration and electrolyte.		Improve stability of a-Si cell and III-V tandem cell. Thin film structure and material selection.		>8% efficient a-Si cell Metal ion catalyst development.		5% efficient nitride-based material. 1 week stability for III-V tandem cells.		10% efficient nitride-based material.		
Year	1997		1998		1999		2000		2001		2002		2003

1 Decision Point: Must achieve 10% efficiency of tandem cell to begin system design effort.

2 Decision Point: Must achieve stability target to move to bench operation.

3 Decision Point: Achieve successful bench operation and prepare scale-up 100W prototype design.

Photobiological Processes

Biological processes for hydrogen production involve the generation of hydrogen from photosynthetic bacteriochlorophyll, carotenoids, etc.) contained in the microorganisms are the light-absorbing material and natural enzymes are used as the water-splitting and hydrogen-producing catalysts (see sidebar on this process below).

Photosynthetic Processes

The conversion of light energy into chemical energy by photosynthetic cyanobacteria and green algae normally occurs according to the following defined steps: (a) light absorption by antenna pigments, and transfer of harvested excitation energy to special pairs of chlorophyll molecules, the reaction centers of photosystem II (PSII), called P680, and photosystem I (PSI), called P700; (b) charge separation at the reaction centers, followed by the linear transfer of electrons (ultimately, through water) through a chain of carriers, concomitant with the formation of a H^+ - gradient across the photosynthetic membrane; (c) utilization of the H^+ - gradient to drive ATP synthesis by a membrane-bound ATPase (not shown below); and (d) dark fixation of CO_2 by the enzymes of the Calvin cycle, using reducing equivalents produced in step (b) and ATP generated in (c). The process in photosynthetic bacteria is analogous to that in algae, except photosystem II and the associated water-splitting function is absent.

Certain algae and photosynthetic bacteria can produce hydrogen under specific conditions. Pigments in algae absorb solar energy and enzymes in the cell act as catalysts to split water into its hydrogen and oxygen components. Bacteria use light and certain waste organic and inorganic compounds in the environment to produce hydrogen.

Research and development in photobiological hydrogen production is focused on elucidating the natural mechanisms at work in these biological systems. The projects in this area are in the early stages of research and development. At present, the maximum energy conversion efficiency reported in a photobiological system, representing the amount of hydrogen energy produced as a percent of incident sunlight energy, is only 5%. These processes require advances in efficiency and reduction in anticipated capital costs to become viable methods for producing hydrogen on a large scale.

Research has focused on two approaches; whole-cell systems involving entire organisms, and cell-free systems that isolate and use only the hydrogen-producing enzymes. The whole-cell systems have potential for near-term production with solar conversion efficiencies of 5% to 30%; the cell-free systems—though scientifically feasible—do not appear potentially cost effective at the current time.

In addition to problems with low conversion efficiencies, nearly all enzymes that evolve hydrogen are also significantly inhibited by oxygen, a by-product of water splitting. There is also the challenge of maintaining biological systems for extended production periods with improved production stability.

Bacterial Water Gas Shift

The goal of this project is to develop a single-step gas conditioning process in the dark for converting raw synthesis gas into a H_2-rich, CO-free gas stream, by using bacteria in a low-temperature catalysis reactor. This process is distinct from the organism's ability to generate hydrogen photobiologically. Current commercial steam methane reforming (SMR) processes use a cascade of water-gas shift reactors to convert CO into H_2. Using the bacterial system, the CO conversion process can be greatly simplified. At biological temperatures ($<60^oC$), the equilibrium of the water-gas shift reaction favors hydrogen production; experiments have shown that inlet CO concentrations of 20% by volume are converted to hydrogen (<0.1 ppm CO remaining) via enzymatic catalysis. The mass transfer of gaseous CO to the bacteria is the rate-limiting step in the conversion process. Bioreactors using vapor-phase and bubble-train designs can significantly enhance shift reaction rates. Additional rate increases are possible through enhancement of the bacterial activity.

DOE is supporting National Renewable Energy Laboratory (NREL, Golden, CO) in the development of bacterial-based systems for the conversion of CO (and water) to H_2 (and CO_2) that are durable, easy to maintain and operate, efficient, and cost effective. Key research areas include improvement of bioreactor designs and biological strains. The project will result in the design, construction, operation, and optimization of bacterial water gas shift technology that will be validated with an industrial partner during the 2002 fiscal year. The fabrication and testing of bench-scale technologies will provide critical information required for scale-up and operation of these plants. Microbial research will be used to enhance the characteristics of the microbial stains through FY 2000. During FY 2001, the construction and operation of the first pilot plant will be completed with reactor operations conducted at moderate pressures and high flow rates.

Hydrogen Production via Bacterial Water Gas Shift

Technology Validation													Construct and operate demonstration plant with industry.
												2	
Subsystem Engineering									Design pilot plant.		Construct and operate pilot plant.		
								1					
Concept Development	Design and build reactor.		Operate reactor continuously @ 0.3 l/min and <10 ppm CO. Scale up bioreactor.		Test reactor designs for improved performance.				Reactor operation for 30+ days.		Reactor operation at moderate pressure and high flow rates.		
Component Research	Identify strains. Reduce CO from 20% to <0.1ppm. CO mass transfer identified as rate limiting step. 0.1 - 0.5 mmol/min/g cells measured for >70 days.		Enhance microbial strain to 4.5 mmol H_2/min/g cells at low cell density.		Enhance microbial strain to 7 mmol H_2/min/g cells at low cell density.		Evaluate improved reactor intervals for CO shift performance. Increase bacterial loading in gas-phase bioreactors by factor of 3.		Enhance microbial strain to 13 mmol H_2/min/g cells at low cell density.		Adapt microbes for moderate pressure and high flow rates.		
Year	1997		1998		1999		2000		2001		2002		2003

1 Decision Point: Economic analysis must indicate potential for commercial success prior to design of pilot plant.

2 Decision Point: Economic analysis must indicate potential for commercial success and industrial partner must be identified prior to design of demonstration plant.

Photobiological Production using Algal Systems

The goal of this project is to develop a solar-driven, direct water-splitting process that produces hydrogen from water using a microalgae system. Photobiological systems, when fully developed, are expected to produce cost-effective, renewable hydrogen. The photosynthetic processes of microorganisms can be up to 20 times more efficient per unit area than trees and other higher plants at converting solar radiation into cell mass and energy. Their successful development could represent a huge source of renewable hydrogen from the sun. Green algae can photoproduce hydrogen directly from water using the reversible hydrogenase enzyme. Hydrogenase-catalyzed hydrogen photoproduction, though potentially very efficient, is currently plagued with two major biological challenges: low light saturation of algal photosynthesis and oxygen-sensitivity of the hydrogenase enzyme. Classical genetic and molecular approaches are being used successfully to address these challenges in the development of commercially viable algal strains. In addition, the large quantities of water that will be required for these systems may necessitate the use of brackish or marine sources, rather than fresh water. Finally, the design of the photobiological reactor system is an important consideration. The use of a single-stage reactor system is operationally attractive, but the co-evolution of hydrogen and oxygen represents a potential safety issue, and requires a gas purification step. A two-stage system, in which hydrogen is evolved in one stage and oxygen is evolved in another, eliminates the need for a gas separation step and is also being examined.

DOE is supporting Hawaii Natural Energy Institute (NHEI, Honolulu, HI), National Renewable Energy Laboratory (NREL, Golden, CO), Oak Ridge National Laboratory (ORNL, Oak Ridge, TN), and the University of California Berkeley (Berkeley, CA) in the development of algal systems that are easy to build, operate, and maintain, and that are efficient and cost effective. Key research areas include improvement in algal performance (O_2 tolerance, light saturation), application of molecular biological techniques, and design and operation of photobioreactors. The project will result in the isolation of mutant algal systems and the development, design, and construction of optimized 1- and 2-stage photobiological reactor prototypes. The operation of the photobioreactors from FY 1999 to 2003 will provide constant feedback to the researchers and will lead to system optimization. Biological research will continue over the FY 1998-2003 timeframe.

Photobiological Production of Hydrogen using Algal Systems

Technology Validation															
Subsystem Engineering													Scale up Hawaii Process.		Optimize Hawaii Process.
										2					
Concept Development	Stage 1 of 2-stage Hawaii Process designed and built.		Operate stage 1 of Hawaii Process.		Optimize stage 1 of Hawaii Process.		Establish 2-stage Hawaii Process.		Operate lab-scale 2-stage Hawaii Process.		Optimize Hawaii Process and include O_2 tolerant mutant.. Evaluate single stage photobioreactor using model organism.		Operate single stage photobioreactor using O_2 tolerant mutant.		Modify photobioreactor designs for marine organisms. Establish CRADA with industrial organization to develop 2-phase NREL/UCB system.
										1		3		4	
Component Research	Isolation of mutant with O_2 I_{50} for hydrogen production >50% higher than parent strain. Operation of single stage laboratory photobioreactor continuously for 18 months using model organism.		Develop molecular biology techniques for isolating superior mutants. Increase H2 production to 70% of photosynthetic capacity. Complete quantum efficiency measurements of PSI/PSI+PSII. 10% reduction of antennae complexes.		2% oxygen tolerant mutant (5 minute life) for a 1-stage system. Identify m-RNA species. 20% reduction of antennae complexes. Demonstrate scientific feasibility of a 1-organism 2-phase system (NREL/UCB)		5% oxygen tolerant mutant (10 minute life) for a 1-stage system. 30% reduction of antennae complexes. Improve switching time for 2- phase NREL/UCB system by 20%.		10% oxygen tolerant mutant (1 hour life) for a 1-stage system. Improve H2 production ratio of NREL/UCB system to 20% of theoretical.		Combine antennae mutant with oxygen-tolerant mutant.		Begin integration of enzyme and removal of antennae complexes in marine organisms. Increase H2 production ratio to 70% of theoretical for NREL/UCB system.		Continue biological research on marine organisms. Improve energy conversion efficiency of NREL/UCB system to 1%.
Year	1997		1998		1999		2000		2001		2002		2003		2003

1 Decision Point: Oxygen tolerance goal must be reached before incorporation into bioreactors can proceed.

2 Decision Point: Successful operation of 2-stage reactor is necessary before design of scale up of the system can begin.

3 Decision Point: Evaluate promise of improving marine organism before modification of photobioreactor design.

4 Decision Point: Evaluate commercial potential of the NREL/UCB system.

4.2 Hydrogen Storage, Distribution, and Delivery Technologies

Strategic Objectives:	**Develop safe and cost-effective storage systems for use in stationary and for on-board vehicle applications.**

Storage Goals:	**Volumetric energy density of 240 kBtu/ft^3, gravimetric energy density of 4 kBtu/lb, Storage efficiency of 75%, cost of storage does not exceed 50% of the cost of delivered hydrogen.**

The storage, transport, and delivery of hydrogen are critical elements in a hydrogen energy system. The goal to develop efficient and cost-effective hydrogen storage systems is driven primarily by the mobile applications for hydrogen, where size and weight of a storage device are major constraints. Other applications will benefit from the technological advances made for on-board hydrogen storage systems. Current technology permits the physical storage, transport, and delivery of hydrogen, in gaseous or liquid form, in tanks and pipeline systems. Compressed gas stored at a pressure of 24.8 MPa (3600 psi) in a conventional fiberglass-wrapped aluminum cylinder has a volumetric hydrogen storage density of ~12 kg of hydrogen per m^3 of storage volume and a gravimetric density of ~2 wt% (grams of hydrogen per gram of system weight [materials plus container]). More expensive carbon fiber-wrapped polymer cylinders achieve higher densities of ~15 kg/m^3 and ~5 wt%, but are still significantly below the target values required for hydrogen to make significant inroads into the transportation sector (62 kg/m^3 and 6.5 wt%).

Hydrogen storage systems have been used in various stationary and mobile demonstrations, but safety remains a major concern—as does the energy input required to charge and maintain hydrogen in a storage device. Stationary storage systems characterized by high efficiency and quick response times will be important for incorporating intermittent PV and wind into the electric grid as base load power.

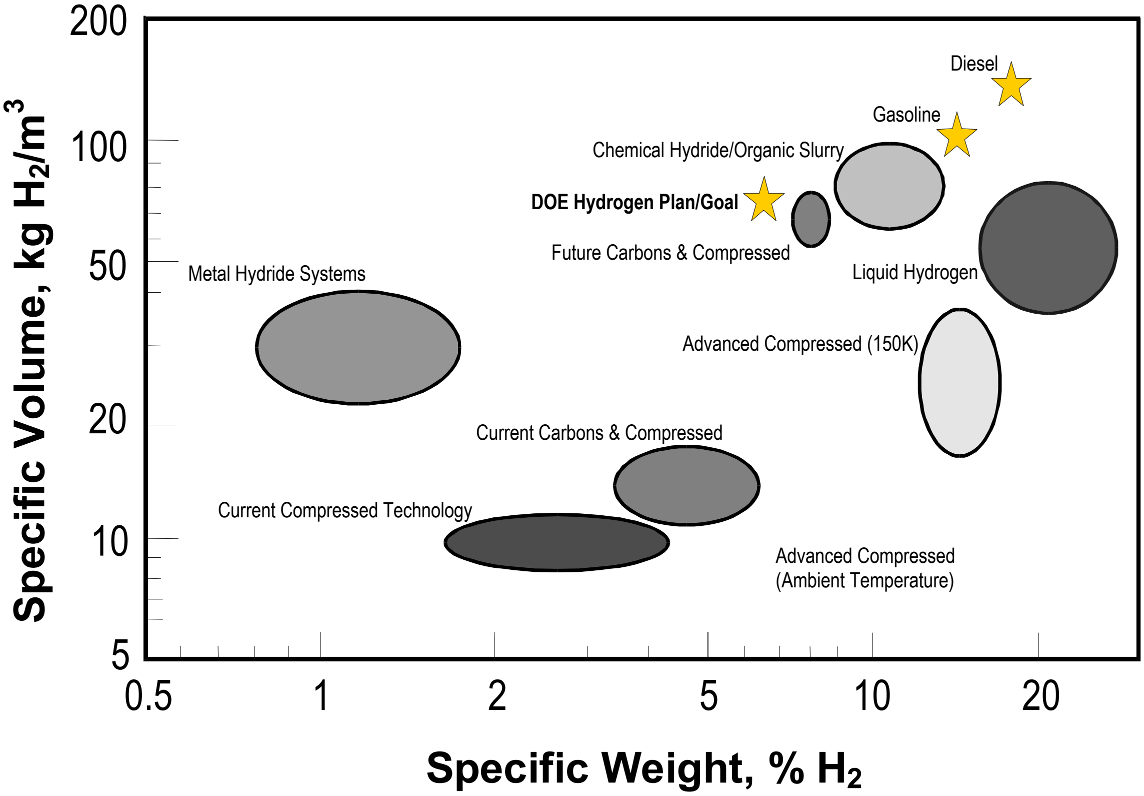
Hydrogen distribution and delivery systems currently available include pipelines, liquid tankers, and compressed gas tube trailers. Other systems that have been under development include glass microspheres, reversible chemical carriers, metal hydride/organic slurries, and iron sponges. Exhibit 7 describes the development status and the research needs for a number of commercially available and future hydrogen storage, distribution, and delivery technologies.

The DOE Hydrogen Program has established technical and cost goals for hydrogen storage technologies. Specific volumetric and gravimetric storage density goals have been formulated for mobile and stationary applications. Exhibit 8 illustrates the relative performance of a number of hydrogen storage technologies compared to Program goals and alternatives. The Program goal for system costs requires that the cost of the storage device should add no more than an additional 50% to the production cost (e.g., if the hydrogen production cost is \$10/GJ, the additional cost for storage should not exceed \$5/GJ).

Exhibit 7: Hydrogen Storage, Transport, and Delivery

Technology	Development Status	Key Research Areas	Validation
Physical Storage			
Compressed Gas	Commercial	Weight and volume, Safety, Compression efficiency, Storage vessel design	This technology is commercial and not included in the Hydrogen Program R&D effort.
Low Pressure Gas Bulk Storage	Commercial	Formation engineering, Remote location	This technology is commercial and not included in the Hydrogen Program R&D effort.
Liquid Hydrogen	Commercial	Liquefaction cost, Dormancy, Safety, Storage vessel design	This technology is commercial and not included in the Hydrogen Program R&D effort.
*Glass Microspheres	System Engineering, System Integration	Heat management, Reprocessing of spheres, Low volumetric energy density	R&D of this technology has been discontinued based on cost and performance evaluation.
*Advanced High Pressure Gas Container Systems	System Engineering, System Integration	Low weight, high pressure and volume vessel design, materials development, optimization of carbon fiber wrapping, pressure vessel stresses and failure analysis.	2003
Chemical Storage			
*Carbon Adsorption	Component Research, Concept Development	Low temperature (active cooling), Impurities, Low volumetric energy density	After 2003
*Metal Hydrides	Concept Development, System Engineering, System Integration	Poisoning of alloy by impurities, Heat management, Weight and volume, Low cost alloys and containers	Build an integrated storage/fuel cell system. 1999
Polyhydride Materials	Concept Development, System Engineering The use of polyhydride materials as catalysts for hydride materials has prompted the refocusing of this research in support of catalyzed hydride development	Optimize aluminate compounds to serve as catalysts.	
Catalyzed Hydride	Concept Development, System Engineering, System Integration	Catalyst and hydride optimization, safety studies, impurity impacts, low cost manufacturing processes, and system engineering.	2000
Other Storage Concepts			
Reversible Chemical Carriers	Component Research, Concept Development	Heat management, Identification of catalysts, toxicity	Based on economic and environmental analysis, this technology does not meet the portfolio requirements of the Hydrogen Program R&D effort.
Chemical Carriers	Component Research, Concept Development	Heat management, catalysts, Temperature reductions	Based on economic and environmental analysis, this technology does not meet the portfolio requirements of the Hydrogen Program R&D effort.
Iron and Water	Component Research	Heat management, weight of system, Identification of catalysts, temperature reductions	Based on economic and environmental analysis, this technology does not meet the portfolio requirements of the Hydrogen Program R&D effort.

Exhibit 8: Storage density chart



Physical Storage

Glass Microspheres

The goal of this project was to develop a novel method of storage using new, high-strength glass microspheres. Glass microspheres filled with pressurized hydrogen achieve densities that permit safe, effective, and economical bulk storage and transport of hydrogen. Commercially produced glass microspheres were studied in the late 1970's for their hydrogen storage potential. These spheres have diameters between 25 to 500 microns and wall thickness of approximately 1 micron. At temperatures of 200 - 400°C, the reduced permeability of the glass permits pressurization with hydrogen. Fill rates are a function of glass properties, and gas permeation, temperature and pressure differential. The commercial spheres are manufactured using a process that sprays glass frits or gels into a furnace. Because of defects in the sphere membrane, the hoop stress at failure of the commercial microspheres is limited to about 50,000 psi.

The Department of Energy had supported W.J. Schafer (San Francisco, CA), Lawrence Livermore National Laboratory (LLNL, Livermore, CA), and Praxair (Danbury, CT) to develop new glass materials and manufacturing processes. The newly engineered microspheres have a theorized hoop stress of about 150,000 psi, permitting a three-fold increase in pressure limit for microspheres of the same dimensions and materials as those commercially available. A bed of microspheres with an average of 50-micrometer-diameter, 1.1-micrometer membrane thickness and 150,000 psi hoop stress at burst pressure, that contains hydrogen at 9000 psi at a 1.5 safety factor, could exhibit a hydrogen mass fraction of 10% and a hydrogen bed density of 20Kg H_2/m^3. Research was aimed at developing small microsphere beds that span a range of glass compositions, packing densities, and particle sizes that will enable the evaluation of the hydrogen storage mass fraction, volumetric density, and loading and unloading kinetics of the system.

As a result of detailed cost and performance analysis performed by Praxair, this project has been suspended.

Hydrogen Storage in Glass Microspheres

Technology Validation											
Subsystem Engineering											
			Project Suspended—see text.								
Concept Development			Scale-up production apparatus to enable the production to control the laboratory production of quality microspheres.								
		1									
Component Research	Conduct testing to optimize glass composition and mircosphere characteristics. Enhance glass permeation through conventional direct heating methods.		Determine mechanisms for enhanced hydrogen diffusion.								
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Determine requirements for safe gas transfer and storage, and parameters for enhanced glass permeation.

Note – Decision point 1 was not met and the fundamental mechanisms of the glass microspheres are not fully understood. The effects of dopants, transient response and energy efficiency were not quantified.

High-Pressure Storage Tanks

The goal of this project is to develop a composite, lightweight storage tank that is impermeable to hydrogen and is applicable to light-duty vehicles and appliances. The challenge is to package high-pressure fuel tanks on-board a vehicle or in a constrained space. The Program is supporting Thiokol (Brigham City, UT) in the development of conformable tanks to address this storage issue.

Based on the physical principle that cylinders efficiently contain internal pressure via membrane response, the conformable tank consists of adjoining cylinder segments with internal web reinforcements, resulting in a multi-cell pressure vessel. The number of cells is optimized for volume. This concept can store up to 50% more fuel than multiple tanks. Six full-size, two-cell tanks will be built in the 1999 fiscal year for testing. The testing includes pressure cycling, flaw tolerance, drop test, penetration, accelerated stress and rupture tests, and environmental tests. During the 2000 fiscal year, the validation of this technology and its system components will be made in collaboration with an industrial partner.

Hydrogen Storage in Pressurized Gas Container Systems

Technology Validation							Conduct Validation of technology and system components with industrial collaborator.				
						3					
Subsystem Engineering					Use accumulated data in the design and fabrication of safe and effective conformable hydrogen storage tanks.						
		1		2							
Concept Development	Fabricate 3 type III composite tanks with Aluminum liners for testing under NGV –2 testing. Fabricate multiple Type IV tanks with plastic liners and unique metal polar boss designs for NGV-2 testing.		Modify existing mold for plastic cylindrical liner to accommodate design revisions. Fabricate redesigned Type IV cylinders and perform leak, burst, and cyclic testing.								
Component Research	Examine the design requirements for pressurized hydrogen storage tanks. Evaluate liner and overwrap materials and design concepts.		Redesign polar boss based on test results. Design reliable and robust tank manifold and ancillary systems. Identify and assess potential hazards.								
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Successfully illustrates that hydrogen tank materials will pass required testing procedures.

2 Decision Point: Demonstrate burst pressures for hydrogen tanks in excess of 5000 psi.

3 Decision Point: Demonstrate burst pressures for hydrogen tanks in excess of 7000 psi from low cost, light weight tanks.

Conformable Hydrogen Storage Tank Systems

Technology Validation		Support/monitor DOE tankage development programs. Actively engaged in design interface between Thiokol (under DOE PRDA) and DOE/Ford demonstration program.	Support DOE programs for development of lightweight tanks. Continue design interface between Thiokol (under DOE PRDA) and DOE/Ford demonstration program.	Support DOE energy storage demonstration programs. Demonstrate adequate temperature, pressure, and humidity cycle life of prototype tanks.	Support DOE programs related to regenerative fuel cells, electrolyzers, and lightweight tanks.	Work with industrial and university collaborators to implement vehicular and other portable power systems using lightweight pressure vessels and lightweight URFCs. Supply tanks for use in URFC system demonstrations.
Subsystem Engineering	Bladders were used as inflatable integral mandrels for fabricating lightweight pressure vessels.	Close collaboration and technical monitoring of Thiokol developments for DOE tankage PRDA.	Test prototype tanks to verify adequately low permeation at ~1% strain. New facility capable of wider range of electrochemical and pressure testing will be brought on line. Close collaboration and technical monitoring of Thiokol.	Improve cycle life of lightweight pressure vessels.	Optimize membrane type and thickness, as well as catalyst choice and loading.	Work with industrial partners to certify lightweight pressure vessels. Certify lightweight pressure vessels to augmented DOT specifications (e.g., NGV2).
Concept Development	Energy storage systems designed for high altitude solar rechargeable aircraft were adapted to automotive use. Initial prototype vessels had estimated performance factors (Pb * V / W) of 4 million cm (1.6 million inches).	Conceived approach to subscale tank development.	Design tank liners that have improved temperature range and stress/strain characteristics.		Work with industrial partners to demonstrate tanks in representative light vehicle service, and design tanks for other applications.	Improve DOT specifications to reflect unique requirements for H2 and O2.
Component Research		Design, fabricate, and test new liner material(s) and use for fabrication of subscale prototype tanks. Produce prototype pressure vessel test articles with new liner materials under contract with Aero Tec Laboratories, Inc.	New generation of liner development under contract with Aero Tec Laboratories, Inc. leads to integrated tank tests.	Downselect advanced liner technologies.	Test multicell URFC stacks of high performance cells with low catalyst loading using H2/O2 and H2/air.	Improve components that limit performance of overall system.
Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**

Chemical Storage

Carbon Structures

Hydrogen Storage in Carbon Nanostructures

The goal of this project is to develop carbon-based hydrogen storage materials that can store significant quantities of hydrogen at room temperature. Currently, compressed gas is the only commercially available method for ambient-temperature hydrogen storage on a vehicle. Carbon nanostructures could yield the technological breakthrough that makes hydrogen-powered vehicles practical. Three types of carbon nanostructures are of interest to the program. The first type, single-walled carbon nanotubes, have elongated pores with diameters of molecular dimensions (several angstroms) and could be ideal for adsorbing hydrogen gases by capillary action at non-cryogenic temperatures. Simple models suggest that hydrogen storage densities ranging from 30 to 54 kg/m^3 and 2 to 5 wt%[3] are feasible, depending on the nanotube diameter. However, gravimetric storage densities ranging from 5 to 10 wt%[3] have been experimentally measured on small samples. The second type of carbon structure of interest to the program is the nanofiber. Interest in carbon nanofiber has increased recently due to reports of hydrogen storage densities of up to 75 wt%[3] near room temperature. Hydrogen reportedly enters the structure between the fiber's graphite platelets, but a mechanism that could stabilize hydrogen at such a high density is currently unknown. The third family of carbon nanostructures is the C60 and C70 fullerene. Although fullerenes can be hydrided to hydrogen levels greater than 6 wt%, the strong H-C chemical bonding involved will require the development of innovative catalytic techniques to liberate that hydrogen at 100-150^{o} C.

DOE is supporting National Renewable Energy Laboratory (NREL, Golden, CO), Oak Ridge National Laboratory (ORNL, Oak Ridge, TN), and Northeastern University (Boston, MA) in the development of compact, lightweight, convenient, and cost-effective carbon-based hydrogen storage systems for transportation applications. Key research areas include the investigation of the interaction between molecular hydrogen and these nanostructures; the fabrication and manipulation of high-yield, high-purity nanostructure samples; and the optimization of hydrogen uptake. Research will result in the design, construction, and operation of a pilot plant for the production of nanostructure storage materials by 2003. The development of continuous production methods for nanotube materials will be initiated in FY 1999, along with the independent verification and analysis of carbon nanofiber storage materials. Continuous production methods and yield rates for nanotube, nanofiber, and fullerene based materials will be improved through the 2001 fiscal year, and cycling and stability tests will be performed. Results from the production, operation, and testing of these carbon nanostructure materials will assist in the design (FY 2002), and the construction and operation (FY 2003) of a nanostructure production pilot plant.

3 Hydrogen/Carbon materials only

Hydrogen Storage in Carbon Nanostructures

Technology Validation													
Subsystem Engineering											Design pilot plant for nanostructure production. Design and build storage subsystem.		Construct and operate pilot plant for nanostructure production. Optimize storage subsystem.
												3	
Concept Development							Continuous production of nanofibers at 50% yield.		Continuous nanofiber production 90% yield @ 1 kg/hr.		Scale up nanostructure production. Cycling and stability testing.		Cycling and stability testing.
				1				2					
Component Research	Demonstrate fundamental physics of carbon adsorption.		Batch nanotube production 75% yield. 2 wt% storage @ room temp (RT). Measurement of hydrogen capacity in nanofibers.		Adsorb 4 wt% H2 at RT and pressure in a system based on carbon nanotubes. Verify reported hydrogen capacity on nanofibers. Establish batch nanofiber production (2B).		4 wt% storage, RT 0.01 gm H_2. Reliability and lifetime analysis. Optimization of nanostructure production and hydrogen storage capacity.		4 wt% storage, RT - 10 gm H_2.		6 wt% storage @ RT.		10 wt% storage @ RT.
Year	1997		1998		1999		2000		2001		2002		2003

1 Decision Point: Must achieve 2 wt% storage to continue project.

2 Decision Point: Must demonstrate continuous nanotube production (2A) and batch nanofiber production (2B) to move to Concept Development stage.

3 Decision Point: Must complete scale up of nanostructure production prior to design of pilot plant.

Hydrogen Storage in Structured Carbon (Fullerenes)

Technology Validation											
Subsystem Engineering									Breadboard performance test and analysis.		Engineering model test and development. Prototype storage equipment test and validation.
								3		4	
Concept Development							Thermomechanical storage element design. Exceed 7wt% storage.		Storage subsystem analysis.		
				1		2					
Component Research	Demonstrate 5.4% H2 storage as C60Hx at high temperature.		Test and analyze catalyst on C60 organic hydride storage at 220^{o}C. Prepare IEA collaboration.		Study of new catalyst through IEA Annex. Continue organic hydride storage to 7wt% at low temperature (≤ 200^{o}C)		Hydrogenation/dehydrogenation cycle test of low temperature catalytic organic hydride.		Long lasting catalyst and catalytic organic hydride experiments.		Materials fabrication and scaling analysis.
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Must achieve 6% wt. Storage density to continue project.

2 Decision Point: Hydriding/dehydriding temperatures less than or equal to 220oC.

3 Decision Point: Must exhibit weight % for H2 greater than 7.0.

4 Decision Point: Must have competitive system performance and meet cost targets for H2 storage.

Hydride Materials

Metal Hydrides

Fuel storage is important to the concept of hydrogen energy systems, and reversible metal hydride storage is one method that can offer compact, safe hydrogen storage. The goal of the hydride projects is to develop a metal hydride that can store over 5 wt% of hydrogen and desorb hydrogen by using the waste heat (about 100^oC) from an associated fuel cell. There are many alloys and intermetallic compounds that combine strong hydriding elements to form alloys. In addition, more advanced materials including multiphase alloys, composites, amorphous and nanocrystalline alloys, polyhydride, and chemical hydrides are considered.

The Department has been supporting Sandia National Laboratory (SNL, Livermore, CA), Energy Conversion Devices (Troy, MI), and the University of Hawaii (Honolulu, HI) to conduct research on different metal hydride alloys, intermetallic compounds, and polyhydrides which could achieve the performance goal. Key research areas include the development of hydride alloys, characterization of the pressure-composition-temperature properties, and the development of prototype tanks. This project will result in the demonstration of improved hydride materials (in excess of 5 wt% at less than 150^oC) and the design and fabrication of lightweight storage modules for fuel cell systems by the end of FY 2000. The design, fabrication, and testing of various hydride tank systems between FY 1998 and FY 2000 will provide critical data for the construction and demonstration of safe, reliable, and effective hydrogen storage options.

Hydrogen Storage in Metal Hydrides

Technology Validation					Build and integrate hydride storage system with a 50 kW fuel cell system.		Build 4 light-weight storage modules with 3.5 wt % hydride storage for a hydrogen bus.					
				3		4						
Subsystem Engineering			Build proto-type phase change hydride storage system.									
Concept Development			Build five storage tanks with 1.5% wt storage for system.		Build light-weight tank with 3.5 wt% storage for system.		Finalize economics based on experimental results.					
		1		2								
Component Research	Hydride formulation, alloying, and polyhydride synthesis. 2 wt% storage, 200^o C.		Demonstrate hydride with 3.5 wt% @, 150^{o}C.		Demonstrate hydride with 5 wt% @ <150^{o}C.							
Year	1997		1998		1999		2000		2001		2002	

1 Decision Point: Must achieve 2 wt% storage @200° C to continue project.

2 Decision Point: Must achieve 3.5 wt% storage @150° C to continue project.

3 Decision Point: Must demonstrate safe, reliable, and effective hydrogen storage in prototype phase-change storage system as need for system integration.

4 Decision Point: Must demonstrate safe, reliable, and effective hydrogen storage in light-weight storage modules, storing 3.5% hydride storage.

Metal Hydride/Organic Slurry Transport and Delivery System

Hydrogen storage and transport as a metal hydride in slurry with an organic carrier offers the potential for a safe and efficient system for delivering high-purity hydrogen. Hydrogen can be released from the metal complex by a number of different chemical reactions and the organic carrier recovered and recycled.

The Program is supporting Tecogen (Waltham, MA) to develop a slurry and to provide the economic analysis to prove the viability of the technology. Research areas include the investigation of calcium and lithium hydrides as hydride carriers, the use and characterization of surfactants as viscosity modifiers, the application of stabilizers to prevent hard settling, and the energy requirements for pumping the different formulations. The project will result in the design and construction of a bench-scale system that will be used to gather scientific and engineering data for optimizing slurry production, pumping, storage, and organic recovery. A detailed engineering study will be completed by FY 2000. Infrastructure issues will be evaluated during FY 2001.

Hydrogen Transport and Delivery in Metal Hydride/Organic Slurry

Technology Validation											
Subsystem Engineering							Conduct detailed engineering study.		Evaluate the infrastructure.		
				2		3		4			
Concept Development			Experimental demonstration of hydrate to hydride. Update economics. Prepare bench scale Hydride slurry system design and test plan.		Conduct bench scale tests of slurry production, pumping and storage and organic recovery.						
		1									
Component Research	Evaluate and make preliminary selection of hydride and organic. Establish H2 generation and production of slurry. Conduct preliminary economic evaluation.										
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Can produce slurry, can generate H2, Economics continue to show promise.

2 Decision Point: Experimental verification of regeneration, Economics continues to show promise.

3 Decision Point: Experimental results continue to show promise.

4 Decision Point: Economics continue to show promise.

Catalyzed Hydride Storage System

Hydrogen storage in catalyzed hydride materials offers the potential for a safe and efficient system for delivering high-purity hydrogen. The Department of Energy is supporting the University of Hawaii in the development of these materials. Recently conducted research has indicated that hydride material, utilizing aluminate compounds as catalysts, offers promise over other hydride systems. This research continues the development of hydride storage materials that contain catalytic additives, which may enable dehydrogenation at temperatures as low as 125°C. Large-scale syntheses of novel alumninate compounds will be conducted as part of this effort for study at Sandia National Laboratory.

Catalyzed Hydride Systems for Hydrogen Storage

Technology Validation							Build/evaluate ICE / genset storage system.		Build/integrate light weight storage system for hydrogen bus.		Build/integrate fuel cell storage system.
						2				4	
Subsystem Engineering					Design/fabricate storage system w/ state-of-the-art hydride/catalyst. Determine cycling, impurity effects, operating parameters.						Safety measure/analysis lifetime measurements.
				1				3			
Concept Development					Safety measure/analysis.		Develop low cost material manufacturing.		Develop low-cost storage system fabrication.		Optimize material properties for fuel cell applications.
						2					
Component Research	Catalyzed hydride concept.		Demonstrate 4+ wt% hydride / catalyst.		Scan for improved hydride. Scan for improved catalyst. Select optium hydrides and catalysts for system performance in excess of 5 wt%.		Demonstrate improved hydride / catalyst.				
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Demonstrate hydrogen storage from catalyzed hydride systems in excess of 4%wt.

2 Decision Point: Identify hydride/catalyst that can improve system performance above 5% wt.

3 Decision Point: System economics meet established cost targets.

4 Decision Point: Materials optimized for fuel cell applications and meet established cost targets.

4.3 Hydrogen Utilization

Strategic Objectives:	**Develop fuel cell and reversible fuel cell technologies as efficient low-cost means of converting hydrogen into electric power.**

Utilization Goals:	**PEM fuel cells that cost <$500 per kilowatt** **PEM fuel cells that produce electricity at $0.045 per kilowatt** **PEM fuel cells that are unpressurized and produce 600 milliamps/cm^2 at 0.6 volts**

Today, hydrogen is used primarily as a chemical in the petrochemical, electronics, and food industries. Because of its potential as a zero-emission fuel, hydrogen use in the transportation and utility sectors is under intense evaluation. Interest has been building for the utilization of hydrogen in internal combustion engines and fuel cells in transportation applications, as well as for electricity generation. The Hydrogen Program conducts fuel cell research on the development of inexpensive, easy-to-manufacture membrane electrode assemblies, and reversible fuel cells for stationary applications. This research effort compliments the fuel cell development programs in the Offices of Fossil Energy and Transportation Technologies. The Hydrogen Program also conducts research and development on the utilization of hydrogen in internal combustion engines and industrial burners. The objectives of combustion are to optimize use of hydrogen and hydrogen-natural gas blended fuels, and to develop the systems and technologies needed to safely and efficiently use hydrogen as a fuel.

Research on fuel cells (see exhibit 9) is intended to develop inexpensive, easy-to-manufacture electrode assemblies.

Safety is an essential element of all hydrogen subsystems. Hydrogen detectors are commercially available, but are expensive. On a large scale, detectors may even serve as ignition points in the event of failure. New sensor designs that rely on more passive and inherently safe designs are under development. Exhibit 10 describes the development status and research needs for a number of end-use technologies and sensor development efforts.

Exhibit 9: Diagram Depicting a Fuel Cell Assembly

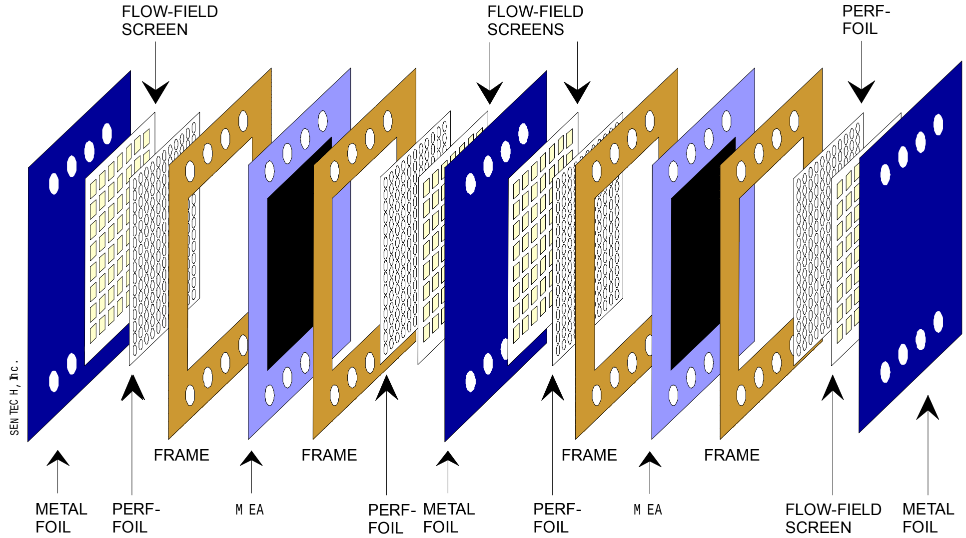


Exhibit 10. Utilization Technologies

Technology	Development Status	Key Research Areas	Validation
Electrochemical Processes			
Phosphoric Acid Fuel Cell	Systems Integration, Commercial	Catalyst Loading, Poisoning, Limited Lifetime, Thermal Cycling, Low Power Densities	This technology is not included in the Hydrogen Program.
Proton Exchange Membrane Fuel Cell	Component Research	Catalyst Poisoning (CO), Platinum and Membranes Costs, Stack Design	2001
Combustion Processes			
Internal Combustion Engine	Component Research, Concept Development, System Integration	Efficient Mixing, Flashback, NO_x Emissions	2001
Turbines/Burners	Component Research	Efficient Mixing, Flashback, NO_x Emissions	The Hydrogen Program has discontinued R&D of this technology (does not meet portfolio req.)
Hydrogen Detection			
Chemochromic Fiber Optics	Component Research, Concept Development	Emissions/Fuel Cell catalyst poisoning from additive diffusion, dispersion	2001
Solid State Sensors			
Colorant/Odorant Addition	Component Research, Concept Development	Poisoning of Chemochromic Catalyst, Kinetics, Selectivity	This technology does not meet current the portfolio requirements of the Hydrogen Program R&D effort.

Electrochemical Processes

Proton Exchange Membrane Fuel Cells

The goal of this project is to develop proton exchange membrane (PEM) fuel cell technologies that will provide low-cost, high-efficient electric power, and can be operated "in reverse" as electrolyzers to produce hydrogen. There has been a significant increase in industrial involvement in PEM fuel cell development for vehicular applications, with a number of demonstration projects throughout North America and Europe. Improvements in catalyst loading requirements, water management, and temperature control have enabled the introduction of these power units in niche markets. In order to increase the market penetration in both the transportation and utility sectors, additional improvements are required. Non-machined stainless steel hardware and membrane electrode assemblies with low catalyst loadings are important areas for cost reductions and efficiency improvements. The most significant barriers to the implementation of low-cost PEM fuel cells are susceptibility of the metal or alloy to corrosion or surface passivation, water management using metal screens as flow fields, and effective stack sealing. Operating the PEM fuel cell "in reverse" as an electrolyzer is possible, but the optimum operating conditions for the power production mode differs greatly from the hydrogen production mode. Specifically, design issues for a reversible fuel cell system are thermal management (effect of temperature on performance), humidification (effect of water supply and distribution on performance), and catalyst type and loading.

DOE is supporting the Los Alamos National Laboratory (LANL, Los Alamos, NM) in the development of PEM fuel cells for utility applications. Key research areas are minimization of machining, reduced catalyst loading, and development of effective water management techniques.

LANL and Plug Power LLC (NY) are partnering in a Collaborative Research And Development Agreement (CRADA) to develop, test, and demonstrate stationary and mobile fuel cell systems with power outputs in the range of 4-5kW (FY 1999), and 10-25 kW (FY 2000) for larger stationary and mobile applications. R&D will focus on manufacturing costs, lifetime, and reliability issues. Together with DCH Technology, Inc. (Valencia, CA), LANL is also developing small (50-500W) fuel cells that operate at atmosphere pressure (air breathing) for remote and /or personal use applications such as remote-located, unmanned instrumentation packages (FY 2001). R&D activities will focus on increasing system-specific power (W/liter) and power density (W/kg). Active feedback controls that maintain optimum performance under a range of operating conditions will also be studied. LANL will incorporate the results of these collaborative programs to optimize fuel cell system performance and manufacturability, and to increase reliability and lifetime while reducing system cost.

The path of this R&D program leads to technology validation and market products based on PEM fuel cells at three important power levels: 50-500W for personal/remote/instrumentation applications, 4 kW for mobile or stationary residential power applications, and 25 kW for larger mobile and stationary (business, small industrial, commercial) applications.

Hydrogen Utilization in Proton Exchange Membrane Fuel Cell R&D

Technology Validation					Transfer all technology to industry.		Transfer all technology to industry.		Transfer all technology to industry.		
						3					
Subsystem Engineering			Fabricate a 4 kW PEM stack (LANL).		Use experimental data from LANL and Plug Power LLC to design an optimum 4 kW stationary PEM fuel cell system (CRADA).		Fabricate 25kW fuel cell for integration into a stationary power system (LANL and Plug Power).		50-500W modular PEM (LANL/DCH).		
						2		5			
Concept Development			Design 4 kW atmospheric PEM system (LANL) Achieve > 300 mA/cm^2 @ 0.7V (57% eff.) and Atmospheric Pressure.		Run 4 kW stack in a mobile and/or stationary platform; collect performance data (LANL). Demonstrate greater than 53% efficiency (hydrogen to electricity).		50-500W modular PEM (LANL/DCH).				
				1		4					
Component Research	Develop metallic bipolar plates (LANL). Develop carbon monoxide tolerant catalysts (LANL and Plug Power).		Optimize membrane thickness and type (LANL and Plug Power).		50-500W modular PEM (LANL/DCH Demonstration).						
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Select stationary or mobile application @ 4-5 kW level.

2 Decision Point: Demonstrate successful operation of system and favorable economics.

3 Decision Point: Successful operation of 25kW unit for large-scale stationary technology validation.

4 Decision Point: Build 5-500W Prototype.

5 Decision Point: Market/manufacture unit.

Regenerative Fuel Cell

Regenerative fuel cell (RFC) systems produce power and electrolyticly regenerate their reactants using stacks of electrochemical cells. Energy storage systems with extremely high specific energy (>400 Wh/kg) have been designed that use lightweight pressure vessels to contain the gases generated by reversible (unitized) regenerative fuel cells (URFCs).

URFC systems coupled with lightweight pressure vessels have been designed for automobiles and are expected to be cost competitive with primary fuel cell powered vehicles that operate on hydrogen/air. URFC-powered vehicles can be safely and rapidly (<5 minutes) refueled from high-pressure hydrogen sources, when available, to achieve driving ranges in excess of 360 miles (600 km). URFC-powered systems could save the consumer the capital cost of a home hydrogen generation unit, since the consumer would be able to electrically recharge at any available electrical source instead of being tethered to a single home electrolysis unit. Such URFC systems could use the existing electrical infrastructure, or a hydrogen infrastructure when available, for rapid refueling. They would enable regenerative braking by electrolysis and power peaking by oxygen supercharging.

This project will test improved cells from industrial partners. LLNL has already demonstrated high cycle life, breakthrough performance, and reduced catalyst loading URFCs. LLNL is working with industrial partners to design/fabricate/test URFC cells with higher performance membranes, higher round-trip efficiency, higher pressure ratings, reduced catalyst loading, and reduced cost. The URFC test rigs at LLNL will be used to performance and cycle test improved URFC cells from industrial partners.

Regenerative Fuel Cell Systems

Technology Validation		Performance and cycle test single cell H2/O2 URFCs from industrial partners at LLNL. Achieved >1.1 A/cm2 (1000 ASF) @ 0.6 V in fuel cell mode for a single cell URFC using H2/O2. Rapid cycling (<1 minute round trip) between electrolyzer and fuel cell modes demonstrated.	Continue to performance and cycle test single cell H2/O2 URFCs from industrial partners at LLNL.		Test multicell URFC stacks of high performance cells with low catalyst loading using H2/O2 and H2/air. Support DOE Programs related to regenerative fuel cells, electrolyzers, and lightweight tanks Work with industrial collaborators to facilitate vehicle demonstrations.	Work with industrial and university collaborators to implement vehicular and other portable power systems using lightweight pressure vessels and lightweight URFCs. Demonstrate packaged URFC systems operating on H2/O2 or H2/air which achieve >400 Wh/kg.
Subsystem Engineering		Determined location of H2/halogen test facility. URFC test rig upgraded to accommodate anode feed electrolysis, in addition to cathode feed electrolysis.	New facility capable of wider range of electrochemical and pressure testing will be brought on line.		Optimize membrane type and thickness, as well as catalyst choice and loading.	
Concept Development	Initiate testing of a URFC cell using H2/O2 as both fuel cell & electrolyzer. Perform test in excess of 2000 cycles with minimal degradation.	Work with industry to improve URFC performance and reduce catalyst loading. Support H2/O2 vs. H2/air trade study. Initiate investigation of reduced catalyst loading for URFC operation.	Design test plan for H2/halogen URFCs.	Conduct Trade study to establish applications where URFCs are advantageous over dedicated fuel cells with and without dedicated electrolyzers.		
Component Research		Investigate alternative membranes and catalysts mixtures to improve performance of URFCs using hydrogen/O2 or hydrogen/air		Collect and compare results obtained using different PEM materials, thickness, catalyst choices, and catalyst loading for URFC's and electrolyzers. Achieve FY 1999 performance goals with 0.5-mg/cm2/electrode catalyst loading.	Test multicell URFC stacks of high performance cells with low catalyst loading using H2/O2 and H2/air.	Improve components that limit performance of overall system.
Year	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**

Combustion Processes

Hydrogen-Fueled Internal Combustion Engine Research

This activity combines highly developed engine component technology with new combustion systems that are optimized for hydrogen to yield robust and inexpensive engines that achieve high efficiency and low emissions. Progressively more sophisticated technologies will build upon existing four-stroke cycle engine research to expand the electrical generation efficiency beyond 50% while maintaining zero emissions. This project approach will develop the combustion systems and improve understanding of the fundamental combustion processes and uses of hydrogen and blended fuels. A combination of experimental investigation and computational modeling will result in an optimized hydrogen-fueled ICE design methodology available to the hydrogen community.

The goal of this work is to develop engine design guidelines for industry that capitalize on the unique combustion characteristics of hydrogen. It is anticipated that these engines will be used to efficiently generate shaft power and electricity with near-zero emissions. This will be accomplished by systematically investigating internal combustion systems configurations that promise to either improve knowledge base or demonstrate unique advantages for improved performance. Questions involving the combustion characteristics as a function of diluent fraction (EGR), equivalence ratio, compression ratio, flame speed, ignition characteristics, and cylinder gas motion (large and small scale) will all be addressed. This program will be performed at Sandia National Laboratory (SNL, Livermore, CA) in collaboration with Lawrence Livermore National laboratory (LLNL, Livermore, CA), which will supply chemical kinetic modeling expertise. University of Miami (Miami, FL) will perform friction reduction and EGR heat exchanger work, and Los Alamos National Laboratory (LANL, Los Alamos, NM) will provide detailed fluid dynamic modeling expertise. SNL will be the program lead and perform the combustion fluid dynamic experimental investigations; University of Miami will perform experiments necessary for the friction reduction work and any experiments necessary for EGR heat exchanger development.

A novel engine configuration is being developed that will solve drawbacks of existing engine configurations for the production of electrical power and will improve the real cycle efficiency. SNL has on record with DOE a Technical Advance (Sandia Disclosure no. 8035) for a rapid combustion homogeneous-charge compression ignition engine concept. This system uses a variable compression ratio free piston, two-stroke engine configuration combined with a linear alternator for electrical power production. In addition to this mechanical simplicity, the free piston reduces the piston residence time at top dead center, reducing the heat transfer into the combustion chamber walls. While the merging of a free piston, linear alternator, and two-stroke cycle is new, each of these technologies has been previously demonstrated independently; thus, the combined combustion performance must be understood. Recent experiments at SNL involving a single stroke free piston combustion experiment have demonstrated a 55% indicated thermal efficiency (ITE) with 2 parts per million NO_x emissions. Based on these results and the low mechanical losses associated with free piston two-stroke cycles, an electricity conversion efficiency of greater than 50% may be possible.

The results of these engine development activities will be developed and deployed into full-scale prototypes by the end of the 2002 fiscal year.

Hydrogen Utilization using Crank Shaft IC Engine Development

Technology Validation							Mini-bus Hybrid Development and Deployment.				Fully integrated Vehicle.
						2				4	
Subsystem Engineering					ICE / Genset Development for selected hybrid deployment.				Operational flex design EGR, 1>ϕ>0.		
				1				3			
Concept Development			Optimize Physics		Dilute operation of high Exhaust Gas Recirculation EGR system, ϕ =@1.		Dilute operation of high EGR, ϕ <1, multi-liquid fuel.				
Component Research	Optimize Physics										
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Reach 47% indirect thermal efficiency for calculated brake efficiency of 40%.

2 Decision Point: Total Efficiency of 38% demonstrated Fuel/electrical output.

3 Decision Point: Complete performance maps for the high dilute EGR <1.

4 Decision Point: Successful completion of integrated system and controls.

Rapid Reaction Homogeneous Charge Compression Ignition Free Piston Generator

Technology Validation							Build/evaluate ICE / genset storage system.		Build full-scale prototype.		Test units in collaboration with OEM.
				3		5,6		8		9	
Subsystem Engineering					Linear alternator fabrication and testing.		Test scavenging Performance.		Build and test control system.		
		1		2,3				7			
Concept Development	56% Efficiency, 0 = NOx Hydrogen HCT Support.		Hydrocarbon Fuels High HC, CO Conversion Catalyst. 30 kW, 0.94% efficiency. Magsoft design tool		KIVA Modeling.		Develop control Algorithms starting procedure.				
Component Research	Combustion System		Linear Alternator. Emission controls.		2 stroke cycle scavenging control system.		Demonstrate improved hydride / catalyst.				
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: Achieve high efficiency energy conversion of 56%.

2 Decision Point: Develop design for linear alternator.

3 Decision Point: High efficiency hydrocarbon fuels.

4 Decision Point: Scavenging design.

5 Decision Point: EZEV level emissions.

6 Decision Point: Alternator demonstrates 30 kW, 95% efficiency.

7 Decision Point: Design Control system.

8 Decision Point: Demonstrate high scavenging efficiency.

9 Decision Point: High Efficiency (50%) Low emissions (EZEV).

Hydrogen Detection

The development of codes and standards for the safe use of hydrogen is an important aspect of the Program, as is the development of reliable, low-cost hydrogen sensors. In conjunction with the National Hydrogen Association (NHA) and the International Standards Organization (ISO), the Hydrogen Program is supporting the development of codes and standards. The Program is also active in the development of the Sourcebook on Hydrogen—which includes existing practices, codes and standards, and procedures—for use by safety officials and project developers. In addition, the Hydrogen Program supports research in the area of hydrogen sensors.

Fiber Optic and Thick Film Sensors

The goal of this project is to develop low-cost hydrogen leak detectors for specific market applications. Conventional hydrogen detectors are bulky, complex, and expensive. They require electrical wiring for control and signal transmission, which could act as an ignition source in the event of failure. These detectors are also susceptible to electromagnetic noise interference. Fiber optic and thick film sensors can provide safe and reliable detection of hydrogen. The fiber optic detector is based upon a reversible change in the optical properties of a thin film applied to the end of an optical fiber. The change in optical properties is detected by a surface plasmon (SP) resonance absorption phenomenon in the sensor coating. The sensor is designed so that the portion of the light beam reflected back to a detector outside the wavelength region of the SP resonance is used as an internal reference signal. The output of the detector is the ratio of the hydrogen-affected optical signal to the reference signal. Because both optical signals are equally affected by any spurious changes in the fiber optic transmission, taking the ratio of these two signals cancels out non-specific transmission changes making the sensor sensitive only to the presence of hydrogen. This feature is particularly important for vehicular applications, where cable twisting and bending, and road vibrations can affect optical transmission. The thick film sensor mechanism is based upon the changes in electrical resistivity of palladium metal corresponding to the amount of absorbed hydrogen. The concentration of hydrogen in the palladium can be measured by the volumetric expansion, resistivity, or potentiometric effects.

DOE is supporting Oak Ridge National Laboratory (ORNL, Oak Ridge, TN) and National Renewable Energy Laboratory (NREL, Golden, CO) in the development of hydrogen detectors that are low-cost, reliable, rugged, and suitably sensitive. Key research areas include material improvements, optimization for hydrogen selectivity, speed of response and recovery, and resistance to degradation.

This project will result in the design, fabrication, optimization, and field testing of the next generation of solid-state (SS) hydrogen detection sensors. The design and optimization of robust fiber optic (FO) sensors utilizing surface plasmon resonance and solid state circuitry will be investigated through FY 2000. During FY 2000 and 2001, the next generation SS sensors will be prototyped, fabricated, and field-tested. Field testing activities for FO sensors (FY 1999) and SS sensors (FY 2000, 2001) will be performed with an industry partner.

Hydrogen Detection using Fiber Optic and Thick Film Sensors

Technology Validation					Field test of FO sensor w/ industry.		Field test of SS sensor w/ industry.		Field test of next generation SS sensor w/ industry.		
						3		4			
Subsystem Engineering			FO prototype design, fabrication, and testing.				SS prototype design, fabrication, and testing.		Next generation SS prototype design, fabrication, and testing.		
				1		2		2			
Concept Development	Design of robust fiber optic (FO) sensor using surface plasmon resonance. Design solid state (SS) sensor.		Optimize FO sensor for speed, sensitivity, and selectivity. Optimize SS sensor.		Optimize next generation SS sensor. Fabricate next generation SS sensor.						
Component Research											
Year	1997		1998		1999		2000		2001		2002

1 Decision Point: FO sensor must have adequate sensitivity, speed, and selectivity in the laboratory environment prior to prototype effort.

2 Decision Point: SS sensor must be optimized prior to prototype effort.

3 Decision Point: FO sensor prototype must exhibit adequate robustness prior to field-testing.

4 Decision Point: SS sensor prototype must exhibit adequate robustness prior to field-testing.

APPENDIX A — Acronyms

Btu	British Thermal Units
CAAA	Clean Air Act Amendments of 1990
CD	Concept Development
COP	Conference of Parties
CR	Component Research
CTI	Climate Technology Initiative
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy (DOE)
EIA	Energy Information Agency
EPA	Environmental Protection Agency
FCCC	Framework Convention on Climate Change
FE	Fossil Energy (DOE)
GHG	Greenhouse Gas
HTAP	Hydrogen Technical Advisory Panel
IA	Implementing Agreement
ICE	Internal Combustion Engine
IEA	International Energy Agency
MSW	Municipal Solid Waste
NASA	National Aeronautics and Space Administration
NHA	National Hydrogen Association
OBT	Office of Building Technology (DOE)
OECD	Organization of Economic Cooperation and Development
OER	Office of Energy Research (DOE)
OPT	Office of Power Technology (DOE)
OTT	Office of Transportation Technology (DOE)
PCAST	President's Committee of Advisors on Science and Technology
POX	Partial Oxidation
R&D	Research and Development
SCF	Standard Cubic Feet
SE	Subsystem Engineering
SER	Sorbent Enhanced Reforming
TV	Technology Validation